INTO
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INTO THE THERMOSPHERE

THE ATMOSPHERE EXPLORERS

NASA SP-490

INTO THE THERMOSPHERE

THE ATMOSPHERE EXPLORERS

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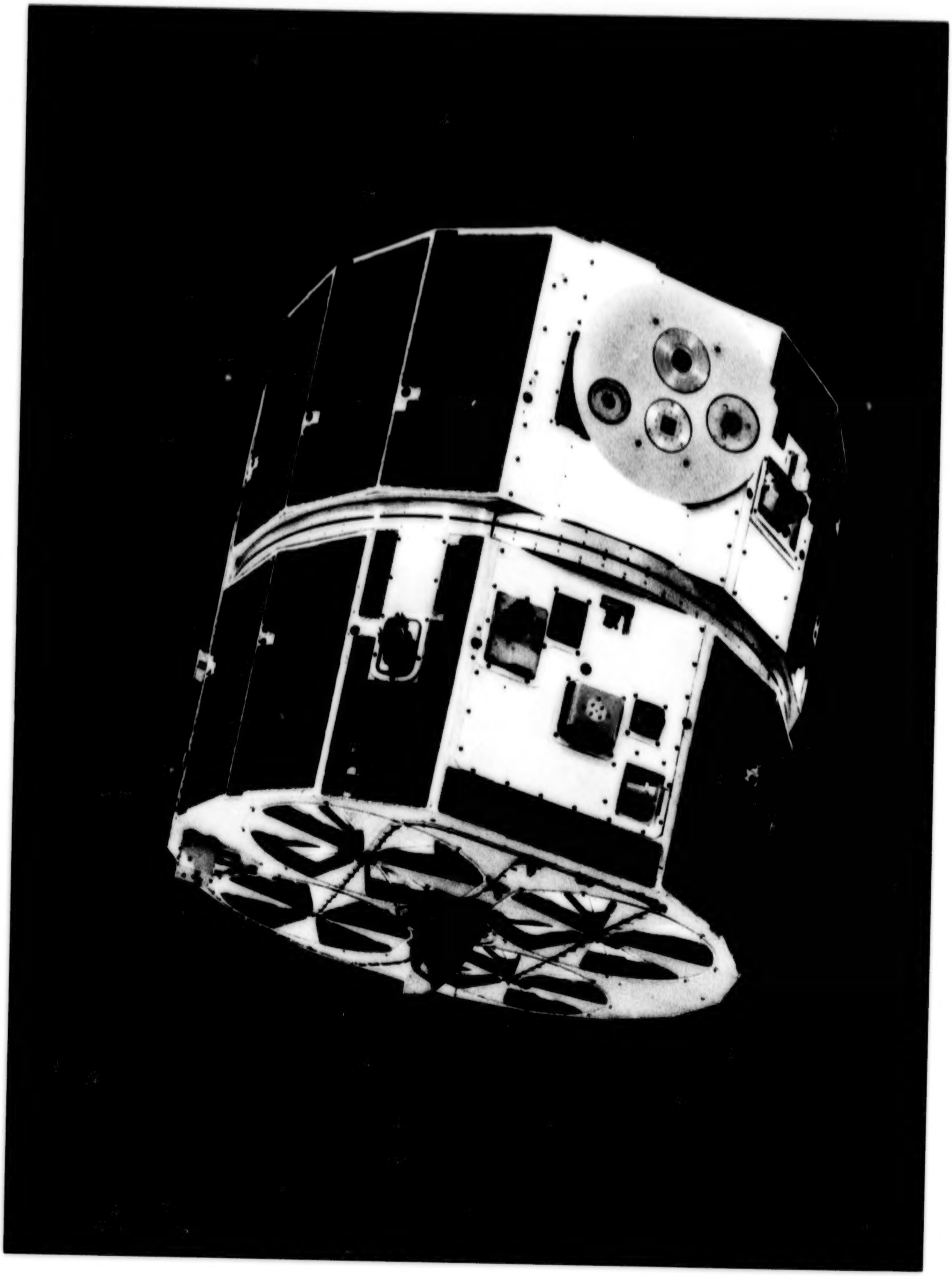

FOREWORD

Too frequently we look on a particular space mission as an event unto itself, one which should lead to great discoveries and revelations of understanding. Too frequently the actual results from a mission meld into the geographically distributed annals of esoteric scientific literature. Too frequently we do not tie off our missions with a summary of lessons learned or how they so tediously really came about, or of the human interactions.

Into the Thermosphere goes far in rectifying those deficiencies. First, we are taken back over 300 years and thence trace the evolution of our discoveries and understanding of the atmosphere, marching along with the scientists and their technology of the day. Indeed, one feels the increased pace of discovery as the world of technology takes off in the early 20th century, pausing occasionally as in the early 1960's and then again expands rapidly with the advent of the satellite.

Step-by-step we see the scientist's involvement go from that of an individual to that of a team participant, instruments evolve from simple to complex, data analysis grows from a reading of a strip chart to interaction with large computers. We see how the bits of data integrate over the years into a scientific comprehension. The Atmospheric Explorers are shown in their relationship to other contemporary missions, particularly Dynamics Explorer and the International Sun-Earth Explorers.

The direct output of our spacecraft and instruments is data. *Into the Thermosphere* leads you through the essential, frequently tedious steps of the entire data acquisition and handling process—necessary but hardly sufficient. I believe the greatest contribution of *Into the Thermosphere* is its lucid explanation of the scientific results, always noting why a certain measurement was made and then tying the diverse experiments together into a coherent model of the thermosphere. One sees, feels, and almost hears the transformation of data into that ultimate product of space exploration—knowledge.

Noel W. Hinners
Director
Goddard Space Flight Center

INTRODUCTION

Atmospheric research using artificial satellites began with the first satellite, the Russian "Sputnik," launched in October 1957. The world was startled by that innovation, and scientists were excited by the clear indication that a new era of scientific research had begun.

Analysis of the decaying orbit of that satellite and its successors led to the first new knowledge of the density of the upper atmosphere since earlier deductions from the observations of meteor trails. A particularly interesting new finding concerned inferences regarding the variations of the atmosphere in response to changes in solar radiation. Deductions of the atmospheric temperature and somewhat speculative estimates of the composition of the atmosphere followed and stimulated new interest in these areas.

When NASA was established about a year later, one of the first areas to which attention was directed was the Earth's atmosphere. A satellite system that would carry instruments appropriate for in situ measurements of atmospheric density and composition was adopted as an element of the newly established NASA Explorer program. In keeping with the nomenclature system of that time, the first satellite was designated S6, which became Explorer 17 when it was launched in 1963. It was followed in 1965 by a similar but significantly improved satellite (S6a) of much greater capability, which was designated Explorer 32.

The Orbiting Geophysical Observatories program, 1964 through 1971, was devoted to conducting many diversified and interrelated experiments in the atmosphere, the magnetosphere, and cislunar space. It provided a substantial increase in our knowledge of the atmosphere above 400 km and revealed surprisingly large variations apparently related to fluctuations in the Sun's ultraviolet emissions. However, the thermosphere, particularly its lower portions, remained largely unknown in the detail necessary for understanding the basic physical behavior of the medium.

The need to study the lower thermosphere with the new instrument, data handling, and spacecraft technology then available led to the formulation and establishment of the Atmosphere Explorer program. This new program included three satellites designated AE3, AE4, and AE5. (The earlier Explorers 17 and 32 were considered to be AE1 and AE2.)

This book provides an overview of the Atmosphere Explorer program with particular emphasis on AE3, AE4, and AE5, which represent early examples of problem-dedicated missions–using a team approach to relate the fluctuating solar ultraviolet input to the neutral atmosphere and the resultant ionization. The Atmosphere Explorer Team, for the first time, included theorists as well as the investigators responsible for making the closely correlated measurements needed for understanding the complexities of the thermosphere.

N. W. Spencer, Project Scientist
E. R. Schmerling, NASA Hq. Program Scientist

CONTENTS

FOREWORD . . . vii

INTRODUCTION . . . ix

CHAPTER 1: ENIGMAS OF THE THERMOSPHERE . . . 3

- Background . . . 3
- Exploration of the Neutral Thermosphere . . . 9
- New Measurements and Evolution of Early Models of the Neutral Thermosphere . . . 11
- The Ionosphere Before Atmosphere Explorer . . . 16
- NASA's Upper Atmosphere Program . . . 22
- NASA's Atmospheric and Space Physics Program . . . 22

CHAPTER 2: OBJECTIVES AND ORBITS . . . 31

- First Aeronomy Satellites . . . 31
- NASA/Goddard Space Flight Center Studies . . . 39
- Contract Awards . . . 42
- The Atmosphere Explorer Organization . . . 43
- Orbits . . . 46
- Mission Science Objectives . . . 51

CHAPTER 3: THE SCIENTIFIC PAYLOAD . . . 55

- Scientific Instrumentation . . . 60
- Solar Ultraviolet Measurements . . . 61
- Spectrophotometer . . . 61
- Filter Photometer . . . 64
- Neutral Particles, Number Densities, and Temperature . . . 64
- Open-Source Neutral Mass Spectrometer . . . 65
- Closed-Source Neutral Mass Spectrometer . . . 66
- Neutral Atmosphere Temperature Experiment . . . 68
- Atmospheric Density Accelerometer . . . 69
- Plasma Measurements . . . 71
- Positive Ion Mass Spectrometer . . . 71
- Magnetic Ion Mass Spectrometer . . . 73

Retarding Potential Analyzer . . . 75
Cylindrical Electrostatic Probe . . . 75
Low-Energy Electron Spectrometer . . . 78
Photoelectron Spectrometer . . . 79
Airglow Radiation . . . 80
Ultraviolet Nitric Oxide Spectrometer . . . 81
Other Instruments . . . 83

CHAPTER 4: THE SPACECRAFT . . . 87

Design Approach and Evolution . . . 88
General Structure . . . 88
Thermal Subsystem . . . 88
Attitude Control Subsystem . . . 89
Orbit-Adjust Propulsion System . . . 92
Power Subsystem . . . 92
Communications and Data Handling . . . 92
Command and Control . . . 93
Launch Vehicles . . . 94

CHAPTER 5: FROM CONCEPT TO EXPLORATION . . . 97

Orbit Phases . . . 101
Data Handling . . . 109

CHAPTER 6: A NEW LOOK AT THE THERMOSPHERE . . . 119

Energetics of the Thermosphere . . . 119
Chemistry of the Thermosphere . . . 122
Photochemistry, Photoelectrons, Heating, and Airglow . . . 125
Neutral Atmosphere Structure and Dynamics . . . 128
Collaborative Studies . . . 132
Epilogue . . . 136

APPENDIX A–ATMOSPHERE EXPLORER PROJECT PERSONNEL . . . 137

APPENDIX B–ATMOSPHERE EXPLORER CONTRACTORS . . . 143

APPENDIX C–BIBLIOGRAPHY . . . 145

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ENIGMAS OF THE THERMOSPHERE

BACKGROUND

The thermosphere includes the region in which the transition from air to space begins. Its importance to conditions in the lower atmosphere that affect our daily lives has only been realized fairly recently. Although they may have witnessed events occurring there, many people have probably never heard of this thermosphere. One of its many-faceted manifestations is the intriguing display of aurorae–the "northern or southern lights." Another is the blazing trails of meteorites, poetically referred to as "shooting" or "falling stars." High in Earth's atmosphere, the thermosphere acts as a giant protective screen in the sky. On it are displayed the effects of many complex interactions that occur high above our heads at the fringe of our atmosphere as Earth is bombarded by particles and radiation from space.

Although the height at which the atmosphere finally merges into interplanetary space is ill defined, the thermosphere may be regarded in the broadest sense as including the last remnant of atmosphere between Earth and space. As such, all radiation that enters the near-terrestrial environment must pass through the thermosphere before penetrating to lower atmospheric levels. This fact determines not only the main characteristics of the thermosphere, but also which particles and what radiation can penetrate from space to lower altitudes and affect us directly.

Throughout the thermosphere, delicately balanced processes are occurring. Often the details of these processes depend on what radiation has been blocked from penetration by the overlying atmosphere. Despite the fact that the thermosphere is so remotely located with respect to the local environment in which we live and breathe, it cannot be safely ignored. All parts of Earth's atmosphere are intimately interconnected. The atmosphere is crucial to life's continued existence on this planet, and the thermosphere has its own claims to relevancy to human well-being, which are discussed later.

A planetary atmosphere is a gaseous envelope that surrounds a world such as Earth, bound to it by the planet's gravitational field. The atmosphere of our planet extends from the surface of Earth's land masses and oceans to great heights, but at about 600 km, the density of the atmosphere is so low that it no longer behaves as a gas in the classical sense of its speeding molecules quickly colliding and rebounding from each other. Instead, each molecule can move along a portion of an elliptical orbit in Earth's gravitational field before encountering another molecule. The height at which the atmosphere finally merges into interplanetary space varies and is not easily defined.

A natural lower boundary of the thermosphere exists at approximately 110 km–at the turbopause, at which atmospheric turbulence is considered to cease. This "boundary" provides a

means of distinguishing the thermosphere from the atmosphere below. However, for nongeophysical reasons, the lower boundary has been placed at approximately 80 km.

Despite the remoteness of the thermosphere from Earth's surface when compared with the troposphere—the region closest to Earth's surface in which we live and experience weather—the thermosphere has commanded a surprising amount of interest among scientists over the last 80 years. It has also offered many enigmas and the stimulating challenge of resolving them. The reason is that the thermosphere possesses several unique properties that revealed its presence at the turn of the century, long before it became technically feasible to study even lower regions of the atmosphere, which are now referred to as the middle atmosphere. As study of the upper atmosphere evolved, the troposphere, or low-lying atmosphere, was regarded primarily as the domain of the meteorologists, whereas atmospheric science, as distinct from meteorology, was born out of studies of the thermosphere. To place the development of our knowledge of the thermosphere in perspective with respect to the rest of the atmosphere, it is important to review the broad features that characterize different regions of the atmosphere as a function of height.

Scientists have identified several regions that have different characteristics (figure 1). Although the atmosphere decreases steadily with height, it is conveniently divided into these regions, which slowly merge into one another and are not distinct "layers" in the usual sense of a layer. Until recently, the region closest to the surface, named the troposphere by Napier Shaw, was the part of our atmosphere that we knew most about. In the troposphere, water vapor and solar heating produce the turbulent conditions that we call weather, and it is in this region that the major cloud systems are confined. In recent years, scientists have discovered

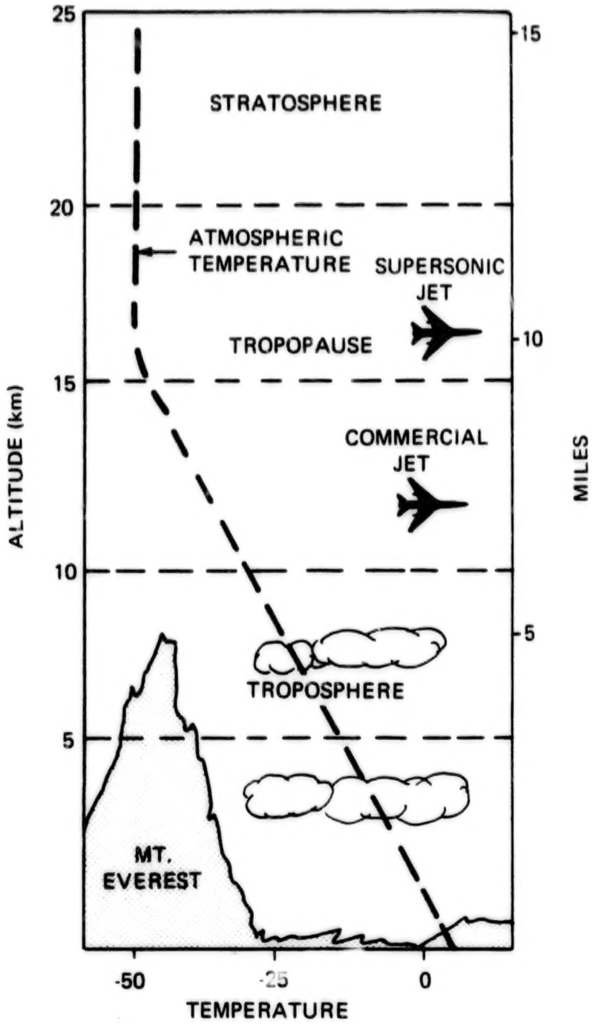

Figure 1. Early investigations of the atmosphere showed that there are at least two regions—the troposphere and the stratosphere—with quite different characteristics.

that weather conditions in the lower atmosphere—conditions that have so many effects on our daily lives—are also influenced by the higher atmosphere.

Not only does the atmosphere support life by providing gases for living things to use in their metabolic processes, but it also protects that life from many hazards of extraterrestrial origin. The atmosphere provides a protective canopy to the Earth, screening its surface from many

meteorites, from harmful electromagnetic radiation, and from many high-energy atomic and subatomic particles.

The study of the upper atmosphere that lies above the troposphere has become an important science that has produced many surprises over recent decades. In particular, over the past few years important questions have arisen concerning our understanding of the middle atmosphere, mainly because of possible serious consequences of human activities. For example, the far-reaching nature of the questions being asked regarding possible damage to the ozone layer—a region that is located in the stratosphere (figure 1)—has brought about a growing realization of how important it is to understand the behavior of the entire atmosphere. If coupling processes exist among different atmospheric regions, and much evidence suggests that they do, we must understand them clearly to avoid irreversible damage to our atmosphere.

Studies of the atmosphere began in earnest in 1643 by a student of Galileo, the Italian scientist Torricelli, who was the first person to realize that the atmosphere must exert a pressure in the sense that we understand pressure today. He reasoned that the weight of all the air in a column stretching up to the top of the atmosphere must exert a force that could be measured by the weight of a column of a liquid (mercury) that it could support (figure 2). From the height of such a mercury column (about 760 mm) he deduced that the pressure of the atmosphere at sea level is about 1.03 kg/m^2. Scientists reasoned that, if such an instrument capable of measuring atmospheric pressure (a barometer) were carried to greater elevations, such as to the top of a mountain, the column of atmosphere above it would be smaller, and consequently, the column of supported mercury would be smaller, thereby showing the reduced pressure.

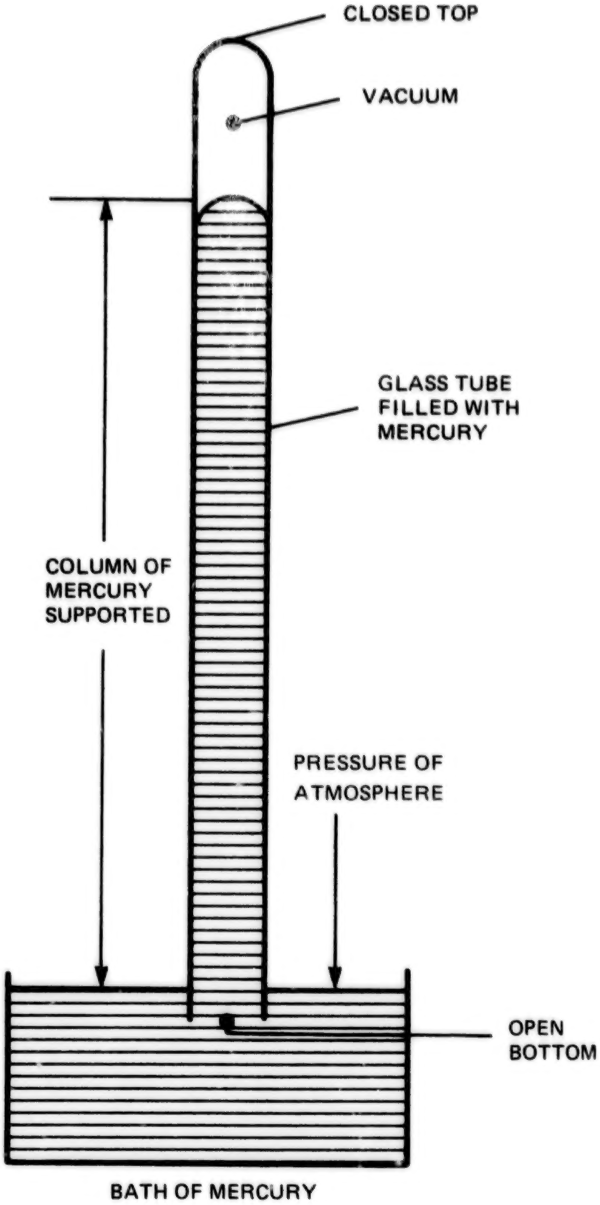

Figure 2. Variations in the pressure of the atmosphere with height above the Earth's surface were traced by mountain climbers using a simple instrument invented by Torricelli in which the atmospheric pressure supports a column of mercury.

To test this theory, the French scientist Pascal carried a Torricelli pressure-measuring instrument to the top of the Puy de Dome in France and measured the pressure there at an elevation of 1465 m. He confirmed that, as expected, the pressure of Earth's atmosphere decreases with

increasing height above Earth's surface. Physicists now call the unit of pressure a pascal (Pa) in his honor. The Earth's mean atmospheric pressure at sea level is 101.325 kilopascals. Atmospheric scientists and high-vacuum engineers who have to measure very low gas pressures use the torr (= 133.32 Pa) in honor of Torricelli. One torr is equal to the pressure exerted by a 1-mm column of mercury. Meteorologists often refer to atmospheric pressure in millibars (mbar). One millibar is a pressure of 1000 dynes per cm^2. Earth's standard atmospheric pressure is internationally agreed on as being 1013.25 mbar, which is the pressure exerted by a 760-mm column of mercury at a temperature of 0°C at standard gravity of 980.665 cm/sec^2 (i.e., 760 torr (table 1)).

Table 1
Pressure Units

1 atm = 760 mm Hg = 101.325 kPa	
	= 1.01325 bar = 760 torr = 1013.25 mbar
1 torr = 1 mm Hg = 133.32 Pa = 0.13332 bar	
1 Pa = 0.00745 mm Hg = 10^{-5} bar	

Human beings live comfortably in the high mountainous regions of Peru at about half the standard atmospheric pressure. Although commercial jets often fly at altitudes at which the pressure is only one-fifth that at sea level, their cabins must be pressurized for passengers to survive. At 50 km, the pressure is about one-thousandth that at sea level (i.e., approximately 1 torr), and at 100 km, the pressure is less than one-millionth that at sea level.

The next major step in defining Earth's atmosphere was made by Edmund Halley, who in 1714 estimated the atmosphere's height as being about 70 km. He did this from observations of meteor trails and the known rate at which atmospheric pressure decreases with altitude as measured by mountain climbers with a barometer. He also said that temperature must decrease by about 10°C for each 160 m of altitude. Halley underestimated the height of the atmosphere because he did not understand how the atmosphere changes at high altitudes. In addition, balloonists found that his theory of a temperature decrease with altitude did not appear to apply universally because they discovered anomalies; warm regions were encountered at high altitudes. These warm regions are called temperature inversions.

By 1893, Hermite and Besancon, by using instrument-carrying balloons known as *balloon sondes* or sounding balloons, had found that at very high altitudes the temperature begins to increase with increasing altitude. Then Teisserenc de Bort suggested that there must be two regions to the atmosphere: (1) a troposphere of turbulent moist air in which temperature on the average decreases with increasing height, and (2) a relatively smooth dry region in which the temperature remains almost constant at 220 K, named the stratosphere by Napier Shaw. But scientists still could not be sure whether there might be regions above the stratosphere in which the temperature might either rise to higher values or plummet to extremes of cold.

An event occurred in 1901 that led to further definition of the high atmosphere. After experiments over shorter distances in Europe, Guglielmo Marconi succeeded in transmitting radio signals across the Atlantic Ocean from Cornwall to Newfoundland. This achievement was difficult to explain because, with the exception of a small amount of bending due to refraction, radio waves travel in straight lines. The question was: How could the radio waves follow the curvature of the Earth's surface for

several thousand miles? The first suggestion of an explanation came independently and almost simultaneously from Oliver Heaviside in England and Arthur Edwin Kennelly in America: that there must be some kind of reflecting layer in the atmosphere overhead. Both scientists realized that this layer must be a conducting region formed by the presence of free electrical charges (ionization) in the upper atmosphere above about 100 km. Heaviside's paper was submitted to *The Electrician* in 1902 but was rejected. Kennelly's paper, however, was published. Strangely enough, the hypothetical reflector became widely known as the Heaviside layer, but it was Kennelly who realized the importance of the layer for studying the high atmosphere. He stated:

> As soon as long-distance wireless waves come under the sway of accurate measurement, we may hope to find from the observed attenuations data for computing the electrical conditions of the upper atmosphere.

The advent of commercial radio followed soon after Marconi's experiment, and methods of measuring the strengths of signals were developed. It was then noticed that the strength varied in a regular way through the diurnal, seasonal, and solar cycles, and the regular daily variation was disturbed during magnetic storms.

Impressive new observations yielded a wealth of data on the amount of ionization present and its height (figure 3). The way then opened for scientists to begin developing theories to account for the presence of the ionization and to develop new techniques for probing this important region of the atmosphere. These early radio experiments revealed that the ionized conduction layer lies in the region of atmosphere that is now termed the thermosphere (including significant charge concentrations).

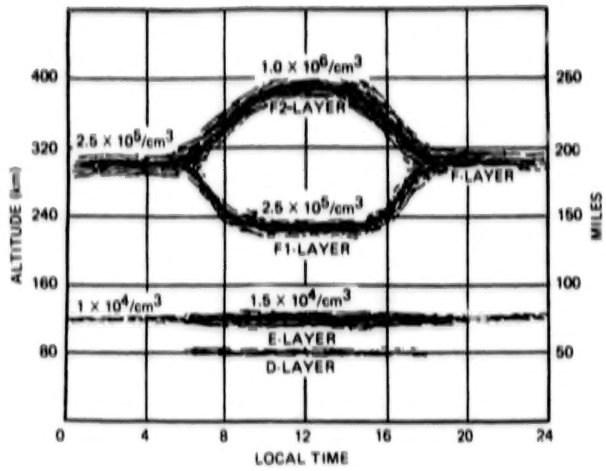

Figure 3. Radio probing of the upper atmosphere from the ground revealed layers of ionization that return radio waves back to the ground.

The discovery of a ground-based means of exploring the thermosphere led to early developments of theories of thermospheric structure and behavior.

Study of the thermosphere began to move ahead rapidly in 1924 when the first dedicated radio experiments were performed with the specific objective of learning more about the ionized component of the atmosphere. The region became known subsequently as the ionosphere. Almost simultaneously, Breit and Tuve in America and Appleton and Barnett in England performed experiments which demonstrated clearly that, even during darkness, a radio wave traveling nearly vertically is, in fact, returned from the Heaviside layer. These were crucial experiments of far-reaching importance for radio communications and for understanding the processes involved. If it should prove feasible to determine the height distribution of ionization at different places, conclusions might be drawn about the atmosphere that had been ionized and about the radiation, presumably of solar origin, that ionized it. Furthermore, if the

ionosphere proved to be a stable phenomenon, successive reflections of radio waves could result in global radio communications.

Radio techniques for exploring the atmosphere have continued to develop at a spectacular pace since the experiments of Breit and Tuve, and remarkable progress in understanding the atmosphere has been made as a result of these techniques. In the early days, radio-reflected waves provided the only means of exploring the high-altitude atmosphere. However, with the development of rockets and satellites, a wealth of new data became available from *in situ* measurements of atmospheric parameters. Nevertheless, despite the advent of the space age, radio engineers were not to be outdone. New and more powerful ground-based techniques of exploring the high atmosphere were devised. Giant radar systems were developed that continue to provide vital information on the behavior of the atmosphere–information that could not be obtained from a space program alone. Working with the network of ground-based installations, the satellite programs have proved to be complementary, if not crucial, to unfolding the nature of the processes that govern the behavior of the thermosphere.

The purpose of this book is to describe the role played by the space program in unraveling the complexities of thermospheric physics and chemistry. In particular, it focuses on the Atmosphere Explorer program, which constituted the National Aeronautics and Space Administration's (NASA's) main thrust in studying the thermosphere during the 1970's.

The early radio experiments, coupled with limited *in situ* rocket and satellite results, led to a surprisingly correct qualitative understanding of the physics and chemistry of the thermosphere. In the early 1960's, however, a stagnation point was reached at which it became impossible to quantify processes further without a completely new approach to the problem. The thermosphere was far too complex to be explained in a unique way. Numerous combinations of different parameters could frequently be incorporated into the theory to yield the correct observational results.

Could science live comfortably with such a state of affairs? To do so would require admitting that scientists have a reasonably good idea of what is going on, but cannot identify with certainty which of several possible processes are actually those that control the behavior of the thermosphere. In other words, theories are not always satisfactory for quantitative predictive work, which is the ultimate objective of all science. For example, radio communications still play a vital role in air and sea traffic. Mediumwave and shortwave radio signals are propagated by reflections from the electrically charged part of the thermosphere that is the ionosphere. Propagation conditions depend significantly on the state of the ionosphere. To improve communications, governments of most countries have established radio frequency prediction services which are equivalent to the weather forecasting services that provide predictions for the troposphere. Current forecasting is done primarily on the basis of empirical models (i.e., predictions are based on past experience (previous observations) and continuing observations). Little or no physics or understanding of the causes of the weather or the ionospheric variations is required to make this type of prediction. However, a far more satisfying and reliable approach would be to develop a thorough understanding of what causes the weather or the ionosphere to change and to predict these changes from a theory based on the underlying physical causes. In the long term, this approach would provide a more dependable service. Much uncertainty in predictions would be eliminated, and intellectual

satisfaction would be derived from the knowledge that we understand more of the complex world in which we live.

We are still a long way from realizing these goals, but significant progress has been made in developing a quantitative understanding of the thermosphere. Later chapters describe the role played by the Atmosphere Explorer program in developing this understanding. The basic approach used to quantify the thermosphere pioneered the data acquisition and analysis techniques for future space missions and constitutes a major aspect of the success of the program in understanding the thermosphere.

EXPLORATION OF THE NEUTRAL THERMOSPHERE

Coordinated exploration of the upper atmosphere began in earnest in 1892 during what was called the First International Polar Year. Researchers all over the world cooperated to investigate, among other subjects, meteorology, the aurora, and geomagnetism. A Second International Polar Year, held in 1933, involved more nations and included studies of ionospheric physics and aeronomy—the investigation of the physics and chemistry of the upper atmosphere.

Rocket exploration of the higher atmospheric regions began in the 1940's with instruments carried aloft by German V2-type rockets and a smaller WAC Corporal rocket developed for the U.S. Army by the Jet Propulsion Laboratory of the California Institute of Technology. Actually, the WAC Corporals were being used before the first firings of the V2 rockets in the United States. An Aerobee series of rockets (figure 4) was later evolved from the WAC Corporal, and these rockets began to replace the V2's in the later 1940's. By 1952, when the V2 program ended, Aerobees, of which there were several improved versions, were carrying payloads of over 60 kg (150 lb) of scientific instruments to altitudes of 240 km—much higher altitudes than could be obtained with balloons. They revealed much new and unexpected information. Other high-altitude rockets were also developed, but the V2's and the Aerobees are particularly interesting because, historically, they were important in the development of *in situ* exploration of the thermosphere by instruments actually carried into the upper atmosphere. Many of the instruments that were ultimately developed for the Atmosphere Explorer program were direct descendants of the sounding rocket instruments.

A Third International Polar Year, scheduled for 1957-58 during a period of maximum activity on the Sun, involved 57 nations. It developed into the first "International Geophysical Year" (IGY). For this event, the available techniques were considerably improved over those of the earlier polar years. One of the significant advances for IGY was the use of sounding rockets on a large scale. Amost 400 were launched, many from high northern latitudes. Although the earlier methods of observation by radio waves and optical techniques were still employed, the sounding rockets allowed measurements to be made by instruments within the thermosphere, albeit for relatively short periods.

Since its beginning in 1958, NASA's sounding rocket activities have generally been spearheaded by university and Goddard Space Flight Center (GSFC) researchers. Also, and beforehand, many other government agencies have conducted sounding rocket research in aeronomy, including the Naval Research Laboratory, Los Alamos Scientific Laboratory, Air Force Cambridge Research Laboratories (which with the National Science Foundation supported extensive university programs), and the Environmental Sciences Services Administration. Many foreign countries also conducted

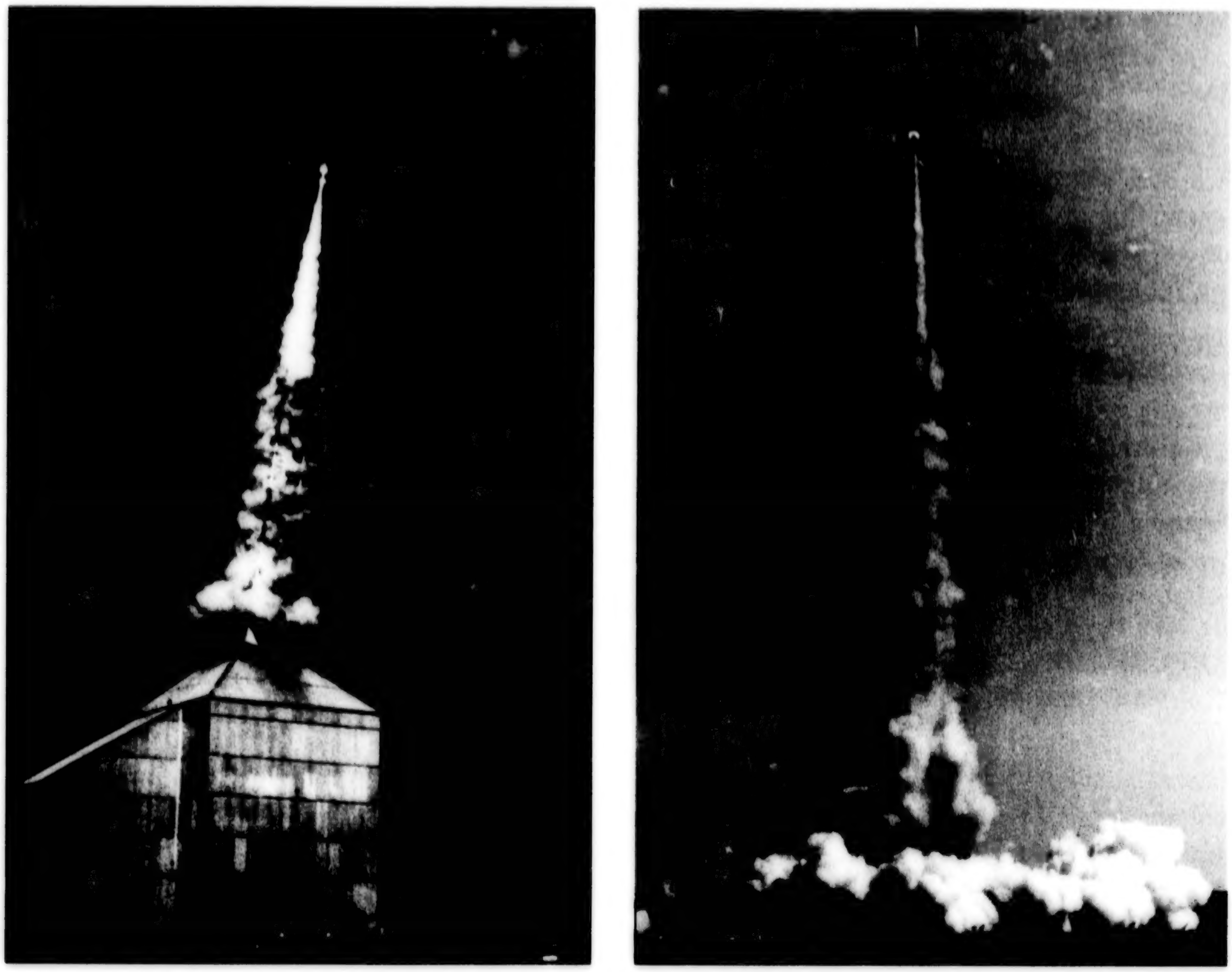

Figure 4. A big advance in exploring the upper atmosphere came soon after World War II through the use of sounding rockets such as the Aerobee.

vigorous upper atmosphere research programs with rockets. NASA has provided international support in the form of technical assistance and, in many cases, the rocket vehicles.

Rocket sounding was followed by observations of artificial satellites and measurements made by instruments carried aboard them high into and above the atmosphere. Although the advent of satellites concentrated attention away from sounding rockets for a time, their intrinsic simplicity, low cost, and ready availability ensured the rockets a continued place in high-altitude exploration. Today, sounding rockets and satellites continue to complement each other's special capabilities.

Satellite experiments have been extremely varied. Many different types of satellites have been used to explore the near environment of the Earth, revealing, in addition to conditions in the upper atmosphere, an environment of energetic charged particles, or plasma, trapped by Earth's magnetic field in a region termed the magnetosphere.

As a result of the sounding rocket and satellite programs, an understanding of the enormous complexity of Earth's atmosphere and its many characteristic regions began to unfold. In addition to the troposphere, stratosphere, mesosphere, thermosphere (figure 5), and ionosphere, scientists have now identified an exosphere and the magnetosphere previously referred to. Characteristics change from region to region according to temperature or density decreases. These "boundaries" are referred to as the tropopause, stratopause, mesopause, thermopause, and magnetopause. As far as the troposphere, stratosphere, and thermosphere are concerned, the divisions of the atmosphere are based on their thermal properties. The troposphere is the region of weather as mentioned earlier. The stratosphere extends from the tropopause to the stratopause where the atmospheric temperature peaks at about 50 km. Above the stratosphere, the mesosphere extends to a height of about 80 km. This region is characterized by a decline in temperature at higher altitudes to a second layer of low temperature at the mesopause. Another important region, the ozonosphere, lies within the stratosphere at an altitude where incoming solar ultraviolet radiation is absorbed and dissociates molecular oxygen into atomic oxygen that later recombines in a three-body reaction with molecular oxygen to produce ozone. This ozone layer is important to screening living things in the lower atmosphere from too much solar ultraviolet radiation that would otherwise destroy them.

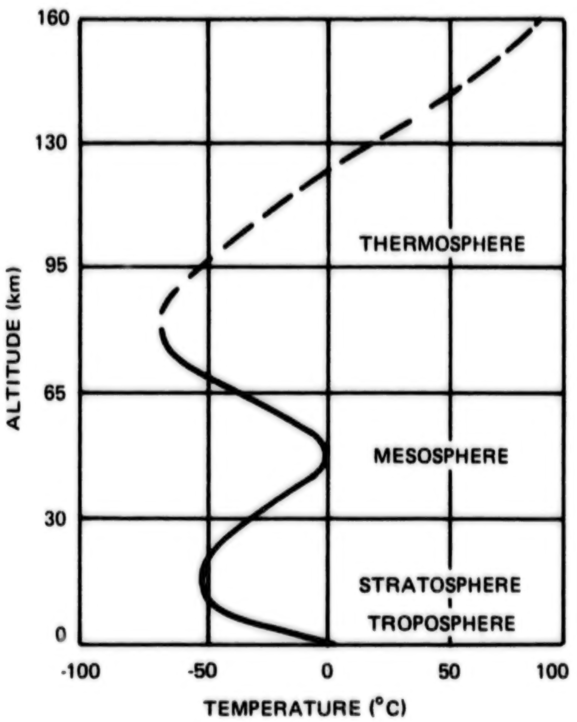

Figure 5. As the higher parts of the atmosphere were later explored by radio, by rocket and balloon probes, and by the observation of natural phenomena such as aurora and meteors, the atmosphere could be thought of in terms of different regions in which different characteristics dominate. Broad divisions are based on temperature.

NEW MEASUREMENTS AND EVOLUTION OF EARLY MODELS OF THE NEUTRAL THERMOSPHERE

In a general description of its physical constitution and chemical composition, Earth's atmosphere may be considered as a perfect gas composed of molecules and atoms, of which only a small proportion consists of charged species that are strongly influenced by the geomagnetic field. The primary properties of the neutral (nonionized) atmosphere are its density, temperature, composition, and motion. Distribution with height of the neutral particles cannot be determined without knowing whether the atmosphere is completely mixed or whether the densities are controlled by chemical reactions or by transport processes (e.g., by winds). Another factor that must be considered is that molecular oxygen and nitrogen can be dissociated into atoms by solar ultraviolet radiation. These atoms may diffuse to greater or lesser heights, or they may recombine by chemical processes.

A profile of atmospheric temperature can be computed if the sources of heat can be identified and if the height at which heat is deposited

can be determined, together with the relative importance of heat removal processes such as radiation, conduction, or convection.

Structure of the atmosphere can be deduced from pressure or density measurements, because density, temperature, and pressure are related by the ideal gas law:

$$p = nkT$$

where

p = pressure
n = concentration
k = a constant
T = temperature

and the hydrostatic or barometric equation relating pressure, density, height, mass, and concentration. The ideal gas law equation simply states that pressure is proportional to density multiplied by temperature. Therefore, if only the pressure is measured, density and temperature are not determined uniquely. The hydrostatic equation states that the rate at which pressure decreases with height is proportional to the density of the atmosphere:

$$-dp/dh = \rho g$$

$$\rho = nm$$

$$H = kT/mg$$

where

h = height

ρ = density

g = acceleration of gravity

These simple equations can be used to deduce how the pressure decreases for a given profile of atmospheric density and temperature. To specify how rapidly the pressure decreases with increasing height, a scale length has been adopted over which the pressure decreases by a fixed amount in height (assuming a constant temperature). Such a height interval is termed a scale height:

$$H = kT/mg$$

The scale height depends on the temperature, mass, and acceleration of gravity. Since the acceleration of gravity remains essentially constant over the height range of the thermosphere, the scale height is constant if the temperature is constant (i.e., the pressure decreases in exactly the same way as the density decreases with height), and the rate of decrease is constant.

Before results can be interpreted meaningfully, the mass to be used in the scale height calculation must be determined. If the atmosphere is mixed completely, an average mass can be used. If no turbulence occurs, the gases will be distributed due to gravity, and each gas will have its own scale height, determined by the mass of a molecule or atom of the gas. Therefore, the numbers of molecules of heavy gases such as molecular nitrogen and oxygen will decrease much more rapidly with height than lighter gases such as atomic oxygen, atomic nitrogen, helium, and hydrogen. Hence, before a model of the neutral atmosphere can be constructed, the following questions must be answered:

- Are the gases mixed or not?
- What is the temperature profile?
- What are the values of density or pressure at some reference level?

Observations of meteor trails and analysis of samples of air collected by sounding rockets established that the atmosphere is turbulent at heights below about 110 km. By releasing material from rockets so that its motion can be

observed from the ground, scientists also showed that turbulence ceases at an altitude close to 110 km, and the change from turbulence to no turbulence occurs in a relatively small layer of less than 100 m. The net effect is that the individual gases comprising the thermosphere decrease in concentration with their own characteristic scale heights (e.g., molecular nitrogen decreases in concentration to about one third every 25 km, whereas atomic oxygen decreases by the same amount every 50 km), but the scale height remains constant only if the temperature remains constant.

Following discovery of the stratosphere, it was believed that the temperature remained constant (approximately 220 K) at all greater heights, and calculations of upper atmosphere pressure were made on this basis. This thought soon proved to be erroneous. In the early 1920's, Lindemann and Dobson deduced theoretically from observations of meteor trails that between 80 and 100 km the air density, and therefore the temperature, must be higher than that calculated from earlier models of the upper atmosphere. Temperature-measuring instruments carried by high-altitude rockets revealed a minimum in temperature at about 80 km, above which theory showed that the temperature increases. Scientists realized that the short wavelengths of solar ultraviolet radiation (less than 1000 angstroms) would be absorbed in the thermosphere (maximum at an altitude of about 140 km), thereby giving rise to the ionosphere with an associated deposition of heat that produces high temperatures there. Longer wavelengths would be absorbed at lower altitudes (in the mesosphere and stratosphere) with significant energy input also in those regions.

The temperature minimum at the base of the thermosphere is caused by two factors:

- The absence of a strong radiation (heat) in this region because short wavelengths are absorbed above it and long wavelengths are absorbed below it
- Cooling by the emission of infrared radiation into space by carbon dioxide, ozone, atomic oxygen, and nitric oxide

This means that there must be a strong flow of heat from the hot thermosphere into the cooler mesosphere where it is lost by radiation. The net effect is that the temperature must increase considerably from the mesosphere to the thermosphere.

Details of what causes the temperature of the thermosphere were not clear until the first satellites were launched in the late 1950's. It was believed that heat could be conveyed from a hot interplanetary gas to the thermosphere, thereby preventing another temperature inversion at high altitudes. Furthermore, as the atmosphere merges with interplanetary space, atoms and molecules experience fewer and fewer collisions and therefore transfer their heat more quickly over long distances. Thus, the heat conduction time in the upper thermosphere is so short that a flat temperature profile above about 200 km was predicted by M. Nicolet. On the other hand, at 120 km, the conduction time is greater than 1 day, so that a large temperature gradient is maintained. This positive temperature gradient is also related to the cessation of turbulence that requires a negative temperature gradient of about 10 K/km.

Early measurements of the upper atmosphere involved relatively sophisticated instrumentation for *in situ* measurements. Beginning in 1945, ionization and other gages, as well as Langmuir probes, were used. The first mass spectrometer was flown about 1948. Complex optical instruments were also employed. Some

initial rocket experiments at lower altitudes simply involved collecting a sample of air for later analysis in laboratories on the ground. A falling sphere method was first used in 1952 to provide information up to 135 km on the density of the lower thermosphere. This method measured the rate of fall of the sphere–the denser the atmosphere, the greater the drag exerted on the sphere and the longer it took to reach the ground.

During the IGY, Luigi Jacchia discovered that the orbits of Earth satellites decay more rapidly than had been expected. His explanation was that the Earth's upper atmosphere is more extensive and denser at high altitudes than scientists had believed from earlier balloon and sounding rocket observations. Significant drag was exerted on the satellites where virtually none had been expected. Because the distortion of orbits by atmospheric drag provides information on the average density of the atmosphere, practically all orbiting spacecraft proved to be useful tools for investigating the characteristics of the atmosphere. A series of high-drag satellites, consisting of essentially large balloons (Explorers IX, XIX, and XXIV), was used to accentuate the drag effects of the rarefied upper atmosphere and more accurately determine its density.

Although most of the new information came from analyzing the drag of a few selected satellites, an important new source of information was initiated in the early 1960's–direct measurements made by instruments carried on board satellites.

Many series of satellites were used to explore the Earth's atmosphere. There were satellites such as Alouette, which investigated the ionosphere by radio sounding the ionosphere from above, similar to the radio sounding from the surface of the Earth. There were the Ionosphere Explorer and International Ionospheric satellites, the Orbiting Geophysical Observatory series, and several international atmospheric and ionospheric investigation satellites (figure 6). However, the main thrust of atmospheric exploration came from the Explorer series, which also investigated the magnetosphere, the interplanetary medium, geodesy, astronomy, micrometeoroids, and energetic particles. Several were aimed at gathering data about the ionosphere, the thermosphere, and the general aeronomy of the atmosphere.

In 1962, Sharp, Hanson, and McKilbon of Lockheed Missiles and Space Company reported atmospheric density measurements during both day and night at about 500 km with a sensitive instrument developed by Dessler and coworkers in 1958. This instrument used a ribbon microphone to determine atmospheric density from the pressure of air on a satellite that resulted from the satellite's velocity through the high atmosphere (ram pressure). In 1964, G. Newton and coworkers reported *in situ* measurements made between about 250 and 330 km with an ion gage on the Explorer XVII. This instrument used a hot filament to ionize the neutral air. The ions were collected, the associated current was measured, and a density was obtained by calibrating the instrument in a laboratory.

The *in situ* measurements roughly confirmed the densities derived from observations of the effects of drag. By 1964, the following facts were established about the higher atmosphere:

- Atmospheric temperature increases drastically between the turbopause at about 110 km and the 200-km level.
- Above 250 km, the temperature is nearly constant.
- Atmospheric constituents are not mixed above 120 km.

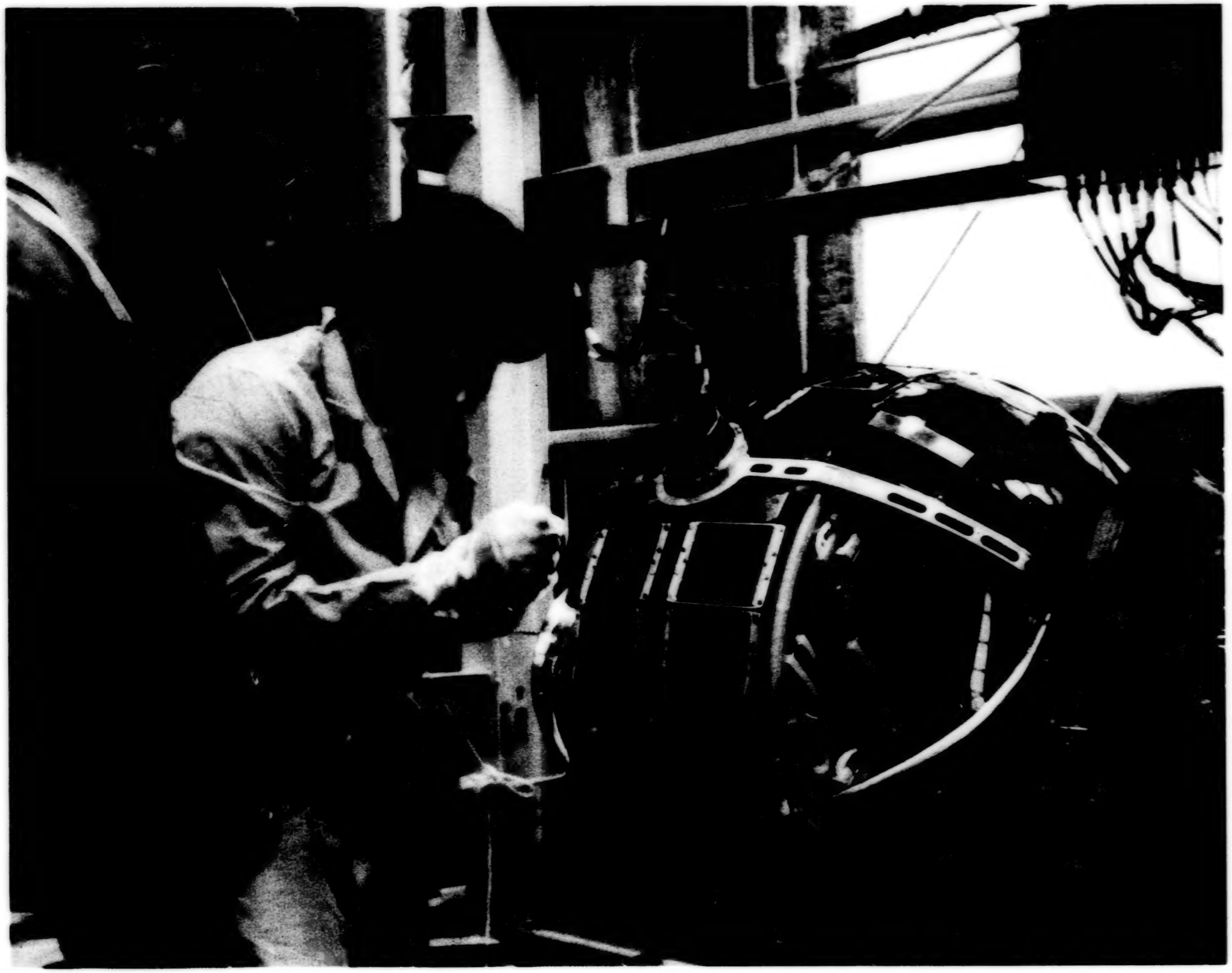

Figure 6. Satellites such as San Marco looked down on the atmosphere and gathered much new information. When satellite orbits decayed because of atmospheric drag, observations of the rate of decay were used to determine the density of the upper atmosphere, which proved to be greater than expected.

- A strong diurnal variation in temperature and density occurs above about 200 km.

- A strong seasonal variation of atmospheric characteristics occurs.

- Density and temperature depend on solar activity and the sunspot cycle.

- A distinct variation of density and temperature occurs with magnetic activity.

These experimental results basically agreed with the behavior predicted by theoretical models of the thermosphere. Before experimental data were available, people who needed to know thermospheric densities or temperatures had to use theoretical values tabulated from the models. I. Harris and W. Priester and D. Bates and M. Nicolet provided some of the earliest models of this type. Early in the 1950's, N. Sissenwine recognized the need for tables of information about the upper atmosphere and organized the U.S. Committee on Extension to the Standard Atmosphere. The *U.S. Extension to the ICAO Standard Atmosphere* was published in 1958. In 1962, the *U.S. Standard Atmosphere* tables, based on the traditional definitions, were produced. These tables were updated by a *Supplement* in 1966 and were revised in 1976 to include information gained from extensive new rocket data, theoretical studies of the mesosphere and the lower thermosphere, and from satellite thermosphere data gathered over a complete solar cycle.

With the availability of the satellite drag data, a new type of model—the empirical model—had emerged. In one of the earliest of these models, devised by L. Jacchia, the variations of density and temperature could be computed for any time of day, season, and level of solar magnetic activity from various indices. For example, by using the time of day, the day of year, and epoch of the solar cycle, the model could produce values of density and temperature for any given level of magnetic activity.

With the experimental information available about the neutral atmosphere in the form of models, quantitative studies of the processes that govern both the neutral and ionized components of the thermosphere became realistic.

THE IONOSPHERE BEFORE ATMOSPHERE EXPLORER

Before the late 1940's, the only information available on the ionosphere came from ground-based radio sounding of the atmosphere over a range of frequencies, with different frequencies penetrating to different layers of ionization. Considerable effort was devoted to determining the concentration of electrons in the thermosphere as a function of height. This kind of measurement yielded only concentrations at heights below the maximum density of the ionosphere. Despite the limitations of the measurement technique, a great deal was learned about the basic physics of the ionosphere and about the basic properties of the neutral atmosphere. Rocket experiments soon began to reveal other details.

The measurements revealed three well-defined layers of ionization, as illustrated in figure 3. These layers were designated the F-, E-, and D-regions from the highest to the lowest, respectively.

Before the composition of the neutral high atmosphere was known, there was only a limited understanding of the ionosphere, and the source of the ionization was not known. Clearly, there was something to be ionized, and there was something, such as energetic radiation, that produced the ionization. Conventionally, the first step in attacking a scientific problem is to begin with the simplest explanation. Presumably, the

source of the radiation lay above the atmosphere, and on impinging on the atmosphere, the radiation stripped electrons from neutral atoms or molecules, thus creating the ions and electrons that formed the ionosphere. Simple calculations indicated that extreme ultraviolet energy from the Sun possessed sufficient energy to do just that.

Obvious candidates for ionization were molecular oxygen (O_2) and nitrogen (N_2). However, if energetic solar extreme ultraviolet photons were present in sufficient numbers to ionize the upper atmosphere, surely there would also be ultraviolet radiation of lesser energy that could still break up oxygen and nitrogen molecules into their atomic constituents (O and N). In addition to oxygen and nitrogen molecular ions, therefore, one would expect the presence in the upper atmosphere of oxygen and nitrogen atomic ions and possibly ions of other minor atmospheric constituents.

Calculating the rates at which ions are produced is difficult because the intensity of solar extreme ultraviolet radiation incident on the atmosphere as a function of energy or of wavelength must be known, as well as how many ions are produced for each photon absorbed. Furthermore, as solar photons penetrate deeper into the atmosphere, they must continuously be absorbed in producing ions and in exciting and dissociating molecules. All these factors must be incorporated into theoretical models. It turns out that practically all the extreme ultraviolet is absorbed in the thermosphere between about 100 and 200 km. This fact makes the thermosphere a very interesting part of the atmosphere. One of the main objectives of the Atmosphere Explorer project was to identify the channels through which this energy flows and to determine the energy fraction which remains in the thermosphere as heat compared with that which is lost to other parts of the atmosphere. Another important objective of the program was to identify all the significant processes that create and destroy ions and to identify the processes that transfer ionization from one species to another. Only by understanding these aspects in detail can the total concentration of ions and electrons be determined by theoretical modeling.

Although much progress in identifying the important processes was made before the first Atmosphere Explorer satellite was launched, quantitative evaluation of the precise role played by each process was not possible. The evolution of models of the ionosphere and the thermosphere before the Atmosphere Explorer illustrates the use of the scientific method. Some of the main developments are reviewed in the following sections.

In 1931, Sydney Chapman developed mathematical models for calculating the ionic production rate as a function of height for different ions resulting from the various atmospheric gases. As mentioned previously, calculating a production rate accurately requires a knowledge of several parameters: the flux (number per second per unit area) of solar photons at each wavelength incident on the atmosphere, the probability (termed a cross section) that a photon of a given wavelength will be absorbed, the probability that it will produce an ion, and the concentration and temperature of the ionizable constituents.

Initially, only rough values were available for these parameters because the solar flux could not be determined accurately except by measuring it outside the atmosphere at all wavelengths. This was not possible before the advent of high-altitude rockets. Cross sections could be theoretically estimated, but the uncertainties in the calculations were so large that laboratory

measurements were essential. The concentrations and temperature of molecular oxygen and nitrogen could be estimated approximately from the theoretical models of the thermosphere. The situation with regard to atomic oxygen and nitrogen was less straightforward because concentrations of those gases, like those of ions, depend on photochemical and transport processes.

Nevertheless, Chapman was able to construct a reasonable picture of the production rates of ions. Electron production is greatest at a level at which the downward increase in gas concentrations is matched by the downward decrease in the strength of the radiation.

Chapman learned several important things as a result of these calculations:

- Production of ions is greatest when the Sun is overhead. When it is at an angle, the extreme solar ultraviolet radiation must pass through more atmosphere to reach the same level and, accordingly, loses more energy higher in the atmosphere.

- In a cool atmosphere, the profile is narrow and long, and the peak ionization occurs at lower heights. In a hot atmosphere, the peak ionization occurs at greater heights, and the curve of its ionization against height is flatter.

Clearly, processes other than the production of ionization must destroy ions, or their concentration would build up indefinitely. Alternatively, the ions could be moved to a different location before their destruction, transported by winds or by electrical fields that would exert forces on the ions that cause them to move. Obviously, processes that would destroy ions would be the reverse of those that produce them (i.e., if the ion encountered one of the free electrons created earlier, the pair could combine to reconstitute the atom or molecule).

Ions and electrons do not recombine immediately after they are formed. Most collisions occur with neutral constituents, and even then electrons may travel hundreds of meters before colliding with an atom or molecule because of the low density. Nevertheless, this is an attractive feature of the ionosphere when it is used as a natural laboratory for the study of rarefield plasma (i.e., gases consisting of charged particles).

Thus, potentially, the atmosphere provides an excellent natural laboratory which can be used to study many chemical processes that are difficult to observe in a ground-based laboratory. At low pressures in a laboratory experiment, reactants collide with the walls of the instrument, making interpretation of results difficult because of the wall effect. A major hurdle to overcome in using the ionosphere as a natural laboratory is carrying aloft the amount of complex instrumentation into this upper atmosphere environment that is necessary for making the measurements.

Before the Atmosphere Explorer program, much effort was expended in perfecting the individual instruments needed for such a laboratory in space. This work took place in different laboratories of the United States and other countries. Instruments were flown and tested individually on many rockets and satellites. The problem was that this approach developed into the *modus operandi*. It would require great effort, foresight, planning, and organizational capability to unify into a single machine the components of hardware and human expertise necessary for simultaneously measuring all the parameters needed to define the state of the

thermosphere at any given instant in space and time. Many people, if not the majority, doubted the feasibility of the concept. It was not simply a question of hardware; the entire philosophy of furthering upper atmospheric science had to be changed. People had to be convinced that the time had come to stop independent individual experimentation and to unite with colleagues, organizers, planners, and funding organizations to aim for a greater goal–a unified plan for understanding the thermosphere.

Despite the importance of solving the problems of the thermosphere, which justified independently the expenditure on the Atmosphere Explorer program, some farsighted people realized that our entire approach to space science must change. To increase the science output per dollar and to break away from a parochial approach was becoming increasingly important. It was becoming necessary to begin viewing the Earth/Sun system as a single problem area, not as numerous independent, unrelated systems, such as the troposphere, stratosphere, mesosphere, thermosphere, magnetosphere, interplanetary space, and the Sun. Philosophically, such a change of attitude is an easy adjustment. As a practical approach to science, however, it is not easy. If the solar/terrestrial system is to be treated as a whole, data must be available for the entire system. Such data would naturally be gathered by many different instruments using widely different methods, but the unified approach demands that: (1) all data must be accessible and available to scientists involved in all the related disciplines, and (2) data should be taken as simultaneously as possible.

If such a grand unification were ever to be realized, a beginning had to be made somewhere. Historically, it happened that the time was ripe to begin with the thermosphere. As was mentioned previously, for example, even the calculation of the ionic production rate requires the simultaneous measurement of three atmospheric parameters: the solar flux, the concentration of neutral gases, and the temperature of these gases. To acquire only these data would require three complex instruments capable of making very accurate measurements in the environment of space and near space. Requirements for a grand unified approach do not stop there. The collaboration of laboratory physicists and atomic and molecular theorists is needed to provide the cross-sectional data at equivalent accuracy and reliability.

In addition to a knowledge of the production rate, many other simultaneous measurements are required. For example, to determine the details of how ionization is destroyed, measurements of the concentrations and temperatures of all the neutral and ionized species that might be involved in those processes are required.

Furthermore, we must know whether the ions and neutrals are being transported either by winds or by electric fields. Therefore, the drift velocities of ions and neutrals must be measured. Even with regard to production rates, we cannot be sure in advance that we have theoretically identified all possible sources of ionization. Energetic (high velocity) charged or neutral particles of local or extraterrestrial origin could be bombarding the atmosphere and creating additional ionization. Instrumentation required to address this difficult question should be capable of measuring the incidence of electrons, light and heavy ions, and neutral particles from low to very high energies.

Clearly, a battery of instruments is required for studying the thermosphere comprehensively. Before such an expenditure of funds can be justified, however, it is essential that the theoretical framework be taken to an advanced level so that precise specifications can be given for instrument and spacecraft design. If this type of integrated approach were attempted during an exploratory phase, we would have no way

of knowing what to expect in terms of detailed behavior, and instruments could not be optimized for the required measurements.

Further discussion of upper atmosphere science before Atmosphere Explorer shows how events evolved to bring thermospheric physics to a point at which the integrated and unified team approach became the next logical step.

In the early models of the ionosphere, theorists realized that different ion species produced in the photoionization process might be responsible for the occurrence of different layers in the ionosphere. Simple models of the dissociation of molecular oxygen by solar ultraviolet radiation, in what is known as the Schumann-Runge continuum, resulted in the production of atomic oxygen. The latter is also produced by dissociative ionization (i.e., where molecular oxygen, for example, is simultaneously dissociated and ionized to yield one oxygen atom and one oxygen ion).

The rate at which oxygen atoms would recombine to form molecular oxygen through collisions was determined theoretically and experimentally to be very slow. Since the concentration of oxygen atoms could not build up indefinitely in the thermosphere, it was realized that these atoms would flow to a region where they can recombine.

Chapman deduced that the oxygen atoms would diffuse downward out of the thermosphere into the mesosphere, where they could recombine in three-body collisions. In the mesosphere, the concentration of oxygen atoms becomes so large that the probability of three bodies colliding simultaneously also becomes quite high. With this model it is possible to estimate the oxygen atom density at the lower boundary of the thermosphere. Because atomic oxygen is not affected by chemistry in the thermosphere, it settles to a profile that is in diffusive equilibrium (i.e., one that decreases in a way that is determined by its own scale height).

One might expect the situation to be similar for atomic nitrogen, but this is not so. Photodissociation of nitrogen molecules is not as significant a process for producing atomic nitrogen. Furthermore, unlike oxygen, the nitrogen atoms react with molecular oxygen in the thermosphere to form nitric oxide (NO). The NO then reacts further with nitrogen atoms, resulting in their mutual destruction with atomic oxygen and molecular nitrogen as products. Therefore, the concentration of atomic nitrogen is only a few percent of the atomic oxygen concentration.

At the base of the thermosphere at 120 km, the concentrations of the three gases–atomic oxygen, molecular oxygen, and molecular nitrogen–are roughly equal at about 10^{10} to 10^{11} per cubic centimeter. Because molecular oxygen and molecular nitrogen are heavier species than atomic oxygen, however, they have a small scale height (i.e., they decrease more rapidly with height). Atomic oxygen and molecular nitrogen are approximately equal at 200 km and, by about 300 km, atomic oxygen becomes the major component of the neutral thermosphere. This is true for altitudes up to nearly 1000 km, at which hydrogen and helium, which are even lighter than atomic oxygen, begin to dominate.

It was soon apparent that atomic oxygen would most likely provide the main source of ions in the upper region of the ionosphere, the F-region. For many years, it was not clear what the significance of atomic nitrogen would be, and it was only after Atmosphere Explorer C was launched in 1973 that a clear picture of atomic nitrogen began to emerge.

Therefore, the first models of the F-region of the ionosphere incorporated photoionization of atomic oxygen as the main source of ionization. At first, the direct recombination of atomic oxygen ions with electrons (as discussed earlier) was believed to constitute the main loss process. However, theoretical calculation by David Bates indicated that this process would occur so slowly that enormous concentrations of electrons should be observed in the F-region. In 1947, he and Harry Massey proposed an alternative scheme that proved to be correct. This scheme introduced the first ionization transfer process into ionospheric chemistry. Bates' theoretical calculations indicated that molecular ions would recombine about 100,000 times faster than atomic oxygen ions. Rapid destruction of atomic oxygen ions could occur by transferring their charges to molecules. Molecular recombination is a different type of process because, on recombination, it involves dissociation of the molecular ion into two neutral atoms. This is written algebraically as follows, using ionized molecular oxygen (O_2^+) as an example:

$$O_2^+ + e \rightarrow O^* + O^*$$

where O^* signifies an excited atom.

Dissociation occurs because, when the extreme ultraviolet solar photon is absorbed in the ionization process, the molecular oxygen ion acquires energy from the photon and this energy must be released on recombination. However, the energy is so great that, if it is retained by the recombined oxygen molecule, this molecule must exist in an excited energetic state. Although such states exist, they are all unstable and lead to quick decay of the molecule into two oxygen atoms. Even this does not use up all the energy contained in the original molecular oxygen ion. What remains goes into two channels: (1) kinetic energy of motion of the oxygen atoms formed, and (2) excited states of the oxygen atoms (denoted by the asterisk).

Kinetic energy of the oxygen atoms is evidenced as fast movement of the atoms. The study of these fast atoms has recently become an area of theoretical and experimental interest.

The energy that goes into exciting the oxygen atoms is responsible for a phenomenon that, before the orbiting of Atmosphere Explorer satellites, was probably studied more extensively, both experimentally and theoretically, than any other thermospheric phenomenon. This phenomenon is the upper atmosphere airglow. The decay of an excited oxygen atom to its normal state results in the emission of photons of airglow, the color of which depends on the specific state of excitation involved. The thermospheric red line at 6300 angstroms is one of the most well known of the atmospheric emissions. At night, the process described above is the main cause of this feature of the night sky. Measurement of the 6300-angstrom airglow from the ground and from space provides a powerful way of studying the processes associated with this emission in the thermosphere.

The study of atmospheric processes in this way is rapidly evolving into a very powerful experimental method known as optical remote sensing. Two special instruments of this type, developed for the Atmosphere Explorers to monitor several of the main thermospheric optical emissions, yielded crucial information on excited species and nitric oxide, information that could not be easily derived from other measurement techniques. Identification of a single additional process in the thermospheric photochemical scheme opened up new areas for measurement and modeling.

NASA's UPPER ATMOSPHERE PROGRAM

NASA's program for understanding the near-space environment has involved three major thrusts: (1) to determine the interactions of the solar wind with the outer boundaries; (2) to determine the interactions of the solar photons with the atmosphere; and (3) to determine how the plasma streams produced by these interactions behave relative to one another. These endeavors include a first phase of exploration and discovery, followed by a systematic survey in which many measurements are taken to determine how all the quantities vary with time and space and with solar activity. The data are then examined in great detail to identify causes and effects in seeking understanding of how and why events occur. Finally, the knowledge is used to help gain an understanding of climate changes and radiowave propagation and to help assess man-made effects on Earth's atmosphere.

Some very practical information emerged from the early exploratory missions into the upper atmosphere. A first surprise followed Project Starfish, the explosion of a nuclear warhead in the upper atmosphere. Most upper atmosphere physicists expected that the effects of the explosion would rapidly dissipate. They were wrong. Another surprise involved Freon and its effects on the upper atmosphere. It seemed inconceivable that a few parts per billion of any substance at a height of 30 km or so would have any serious consequences. Physicists were again surprised and began to ask major questions as to whether trace substances released from widespread uses in agriculture might produce major changes to Earth's climate and surface environment. A third surprise was that electrical powerlines strung all over the world affect the ionosphere by perturbing charged particles at very high altitudes in a way that disturbs the magnetosphere.

Magnetic storms have interfered with power transmission systems, produced electrical outages, and caused failure of communications. In addition, the Alaska pipeline becomes electrically charged during auroral storms and had to be protected from these charges. The initial discoveries about the upper atmosphere have been intriguing. They were followed by the second stage of acquiring more detailed survey information so that more specific questions could be asked.

The theme of all these activities is to attempt to better understand our environment. Thus far, we have unraveled the basic chemistry of the upper atmosphere, particularly the chemistry of the nitrogen and oxygen that are present there. We have looked at the way in which solar photons ionize and heat the plasma of the high atmosphere. We have charted the way in which energy flows through the atmosphere and have found that, even below 200 km, the atmosphere is affected by particles from the auroral zones and by tidal and wave motions.

An important understanding has been that the regions of the atmosphere cannot be studied independently of each other because they interact in many ways. The Earth's environment is large, complex, and dynamically fluctuating (figure 7). Many measurements are needed to obtain a good grasp of its characteristics. Then comes the hard work of trying to understand how all the pieces are formed, how they vary, and what processes control the system.

NASA's ATMOSPHERIC AND SPACE PHYSICS PROGRAM

NASA's programs for understanding Earth's space environment consist of a three-pronged effort (figure 8). One group of investigations studies how and why the solar wind governs the Earth's magnetosphere. Another studies

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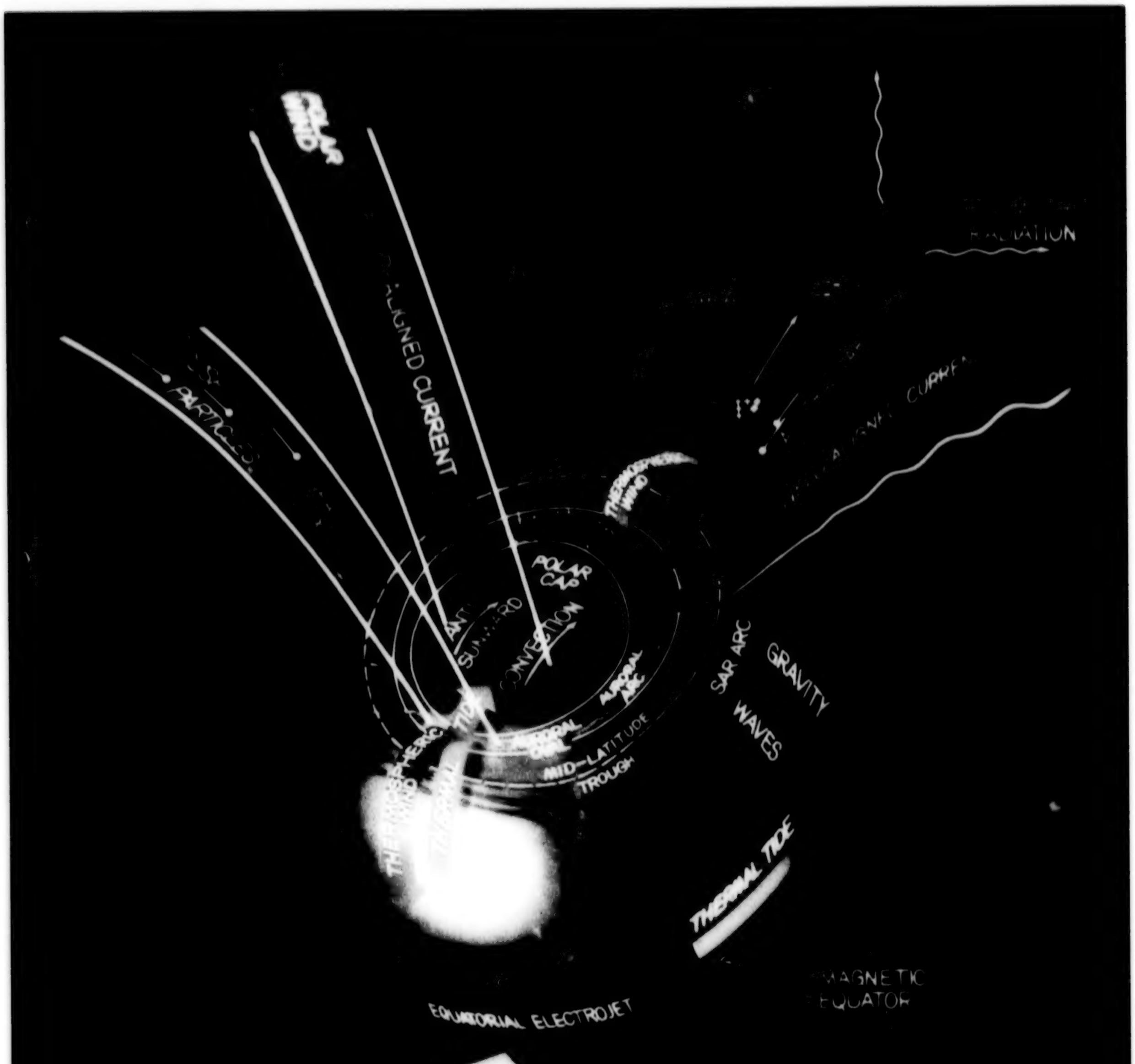

Figure 7. The region surrounding Earth proved to be extremely complex. This artist's conception illustrates the close environment.

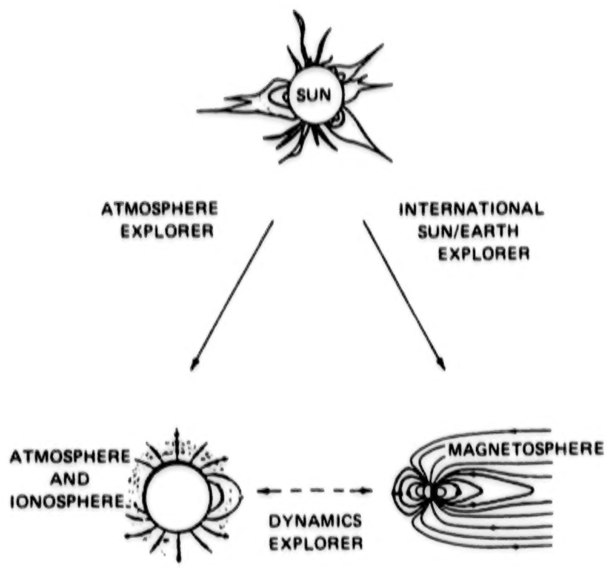

Figure 8. NASA uses three types of satellites to study Earth's space environment.

how and why solar X-rays and ultraviolet radiation transfer energy to the thermosphere. A third group studies how and why the hot tenuous plasmas of the magnetosphere interact with the cooler plasmas of the thermosphere.

The program seeks to improve our understanding of how the forces created by these interactions drive a vast system of electric currents, release corpuscular energies, and impel a flow of mass through the atmosphere and the magnetosphere. In addition, we want to know the details of the processes that result in intense local heating of the atmosphere, neutral winds of high speed, unusual changes in the composition of the atmosphere, auroral displays, and a variety of plasma waves, radio emissions, and airglows.

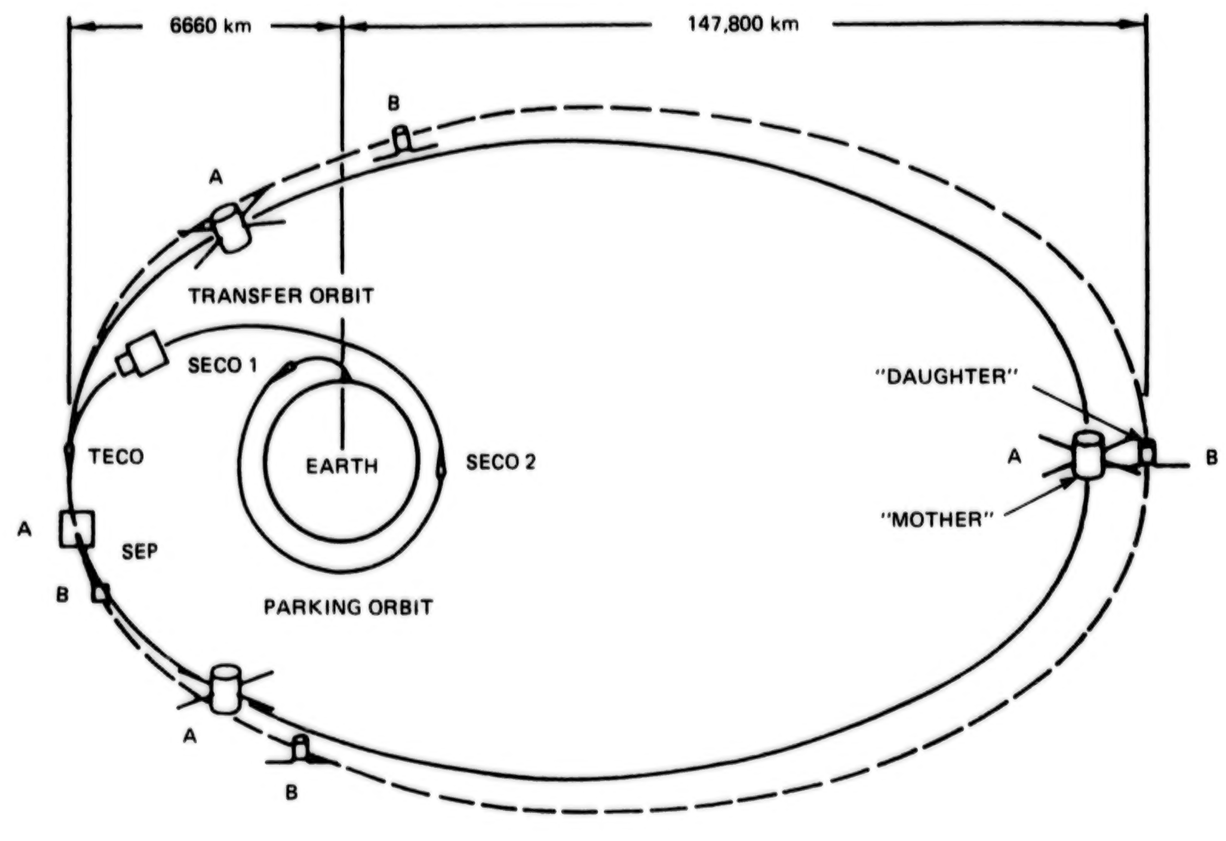

Figure 9. ISEE continued investigation of the magnetosphere to determine how the incoming solar radiation and particles affect this part of Earth's environment.

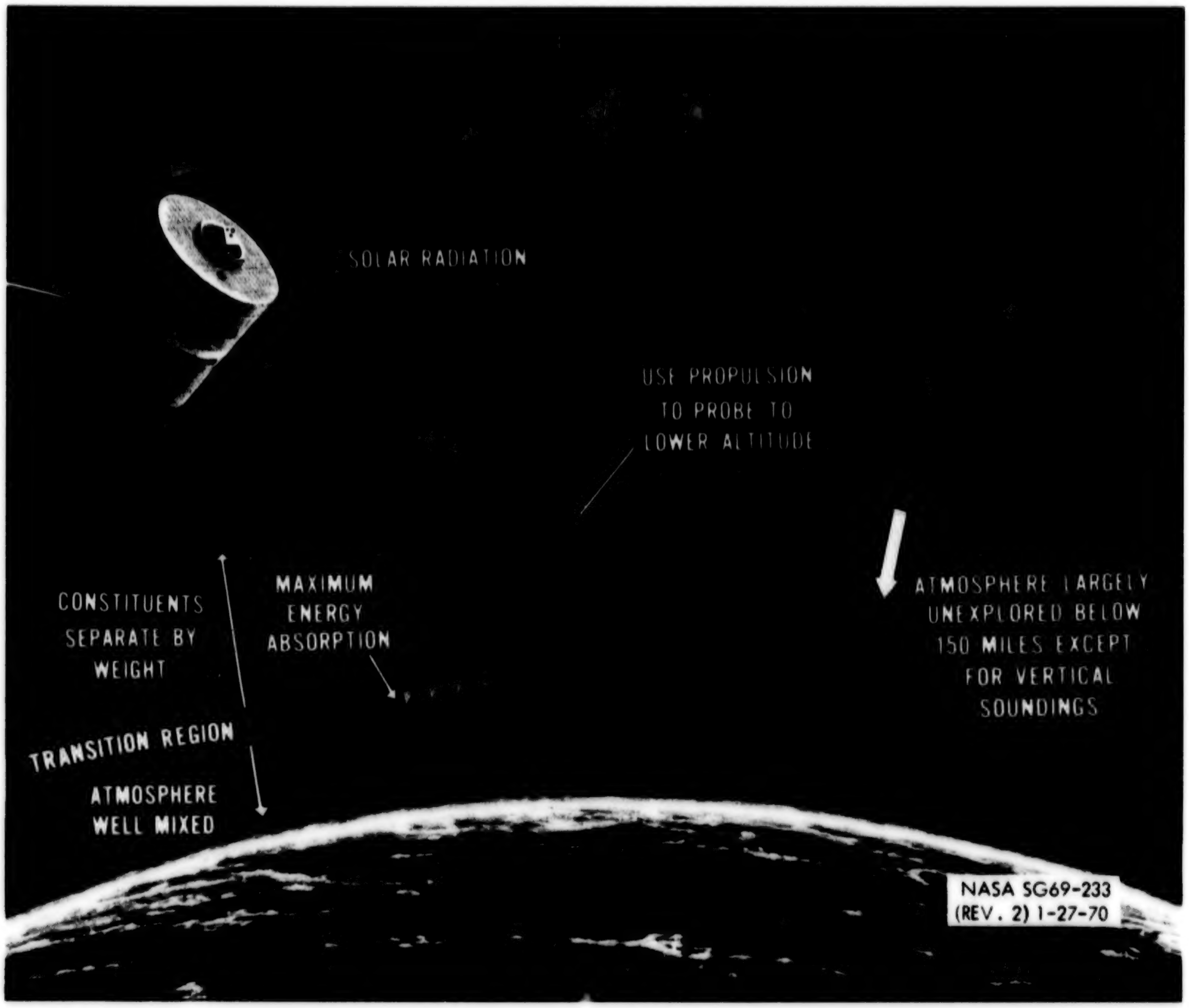

Figure 10. Atmosphere Explorer satellites were used to investigate how solar ultraviolet radiation produces the thermosphere and its ionosphere.

The atmospheric and space physics program relies on three major types of spacecraft investigations. To explore the thermosphere, NASA used a series of Atmosphere Explorer satellites, as described in this document. The International Sun/Earth Explorer (ISEE) satellite (figure 9) and other satellites have investigated the magnetosphere, and the Dynamic Explorer satellites have studied the interactions between the magnetosphere and the thermosphere. New active experiments and remote sensing programs are progressing for the shuttle and space station.

The Atmosphere Explorer satellites (figure 10) marked a new approach in scientific spacecraft. They differed in the orbit flown, the team approach taken by the investigators, and the rapidity with which data from their science instruments were processed, analyzed, and made available to all the investigators on demand. The major innovation of these satellites was their ability to make measurements deep within the thermosphere through the use of rocket thrusters aboard the spacecraft. These thrusters made it possible for the satellite

to maintain its orbit regardless of the braking caused by atmospheric drag at the low altitudes to which the satellites penetrated. The altitude range of primary interest for measurements was from 500 to 150 km, but the spacecraft could penetrate in brief excursions to 130 km when specific measurements were needed.

At the beginning of the Atmosphere Explorer program in 1964, many facts had already been discovered about the upper atmosphere, but they were of a fairly general nature. The distribution of temperature, for example, was known to be isothermal above about 300 km, but the temperature was quite variable, ranging from 700 to 1800 K and sometimes reaching higher values and varying over the 11-year sunspot cycle. It was also known that the daily maximum varies from 1.3 to 1.5 times the minimum nighttime temperature and that seasonal variations occur.

The temperature of the mesopause also varies seasonally, being highest at high latitudes in winter and lowest in the summer. Noctilucent clouds proved to be associated with the very low summer temperatures. The electron temperature is often greater than the temperature of the neutral atmosphere in and above the F-region.

In the thermosphere where the gas particles are relatively few and collide with other gas particles only infrequently, the lighter gases float above heavier gases. Hydrogen and helium are found at very high altitudes. In the lower thermosphere and below, however, considerable mixing occurs as a result of eddies and winds caused by solar heating and turbulence below.

The density of the upper atmosphere has proved to be very variable, mainly because of the day/night temperature variation. This variation in density causes the atmosphere to bulge on Earth's dayside, the maximum occurring at early afternoon.

Motions in the upper atmosphere proved to be very complex. Strong motions result from gravity waves that originate as relatively small pressure changes in the lower atmosphere and increase enormously in amplitude as they move to high altitudes. Although some evidence had been accumulated for a large-scale circulation in the upper atmosphere, details were not clear. Near an altitude of 150 km, winds appeared to flow toward the Equator from the poles.

Rocket flights had mapped the way in which airglow emissions from atomic oxygen and nitrogen varied at different altitudes, and the cause of the emissions had been identified as two-step processes and ion recombinations. In addition, observations had inferred movement of particles from the auroral regions to the radiation belts, but the way in which the auroral particles are accelerated could not be explained. Auroral current systems were believed to result from daily disruption of the magnetosphere and the resultant separation of trapped particles from the charged medium of the outer ionosphere that normally would neutralize them.

The objective of the three Atmosphere Explorers, which were capable of dipping into the atmosphere, was to provide measurements for studying composition and processes within the thermosphere, such as ion and neutral composition and reaction rates, energetics of the ionized atmosphere, processes that control the low-energy electrons, and processes of airglow excitation. Another objective of the satellites was to provide measurements for studying the global structure and dynamics of the neutral atmosphere and ionosphere.

For this purpose, each spacecraft carried more than twelve scientific instruments. These instruments simultaneously measured incoming solar radiation and the atmosphere to provide information about the physical processes that

govern the composition of the lower thermosphere and the ionosphere. The measurements made possible a study of the closely interlocked cause-and-effect relationships that control the near-space environment of Earth. The instruments included spectrophotometers, photometers, spectrometers, electrostatic probes, accelerometers, retarding potential analyzers, and ultraviolet radiation monitors.

Following the success of two earlier Atmosphere Explorers (17 and 32), three missions were planned for spacecraft equipped with onboard propulsion systems to compensate for atmospheric drag. The first, whose orbit ($i = 68°$) was selected so that the perigee would move very slowly, concentrated on gathering data over a wide range of altitudes. The second and third spacecraft orbits (90 and 19 degrees) were designed to study the thermosphere over a wide range of latitudes and local time variations, respectively.

The second part of the NASA scientific satellite triad consisted of International Sun/Earth Explorers. These satellites continued the work that had begun with earlier satellites to explore the interaction of the solar wind with the magnetosphere. Two spacecraft were carried aboard one launch vehicle: ISEE-A managed by NASA, and ISEE-B managed by the European Space Agency. Both these spacecraft followed looping trajectories around the Earth, ranging in distance from 140,000 to 280 km. The use of two spacecraft in orbit at the same time permitted a study of boundaries in near-Earth space–the plasmapause, the magnetopause, the bow shock, and the Earth's magnetic tail–and provided some separation between time and space variables by comparing the measurements from the twin spacecraft.

The scientific instruments carried by these spacecraft were many times more sensitive than those in earlier spacecraft that had explored this important region. The scientific payload consisted of instruments for measuring fast-moving electrons and ions, low- and high-energy protons and electrons, magnetic fields, plasma waves and plasma density, cosmic rays and gamma rays, electric fields, composition of ions, and the propagation of very low frequency radio signals from the Earth to the satellites.

A third spacecraft, ISEE-C, was launched separately and was positioned at a libration point about 1.5 million km from Earth toward the Sun so that it remained between Earth and the Sun and could monitor the fluctuating solar wind about 1 hour before the particles flowed past the inner satellites close to Earth. The ISEE program was also planned to fit into an International Magnetospheric Study during which ground stations, sounding rockets, balloons, aircraft, and satellites viewed the same phenomena simultaneously from different parts of the Earth and from space.

The Dynamics Explorer program complemented the other two programs. It used a high-altitude satellite and a low-altitude satellite, both placed in polar orbits. The aim was to measure electric-field-induced convection, magnetosphere and ionosphere electric currents, direct energy coupling, mass coupling, and wave/particle/plasma interactions. The basic task was to determine how energy is imparted to Earth's atmosphere. The scientific objective was to view the strong interactive processes that couple the hot, tenuous convecting plasmas of the magnetosphere to the cooler, denser plasmas and gases corotating with the Earth–the ionosphere, the upper atmosphere, and the plasmasphere.

Scientific instruments carried by the Dynamic Explorers included a Langmuir probe, mass spectrometers, a retarding potential analyzer, an ion drift meter, low-altitude plasma and high-altitude plasma instruments, proton and

electron detectors, an ion composition spectrometer, an elemental composition analyzer, a neutral atmosphere wind and temperature spectrometer, electric field instruments, a magnetic field instrument, a plasma wave instrument, auroral photometers, interferometers, neutral wind instruments, and a very low frequency radio experiment for determining wave/particle interactions.

This document describes the first part of the three-pronged drive toward understanding the environment of the Earth. It relates the background, operations, and results of the Atmosphere Explorer program that investigated the important region of the thermosphere, a region that presented so many intriguing problems to physicists studying the upper atmosphere of our planet.

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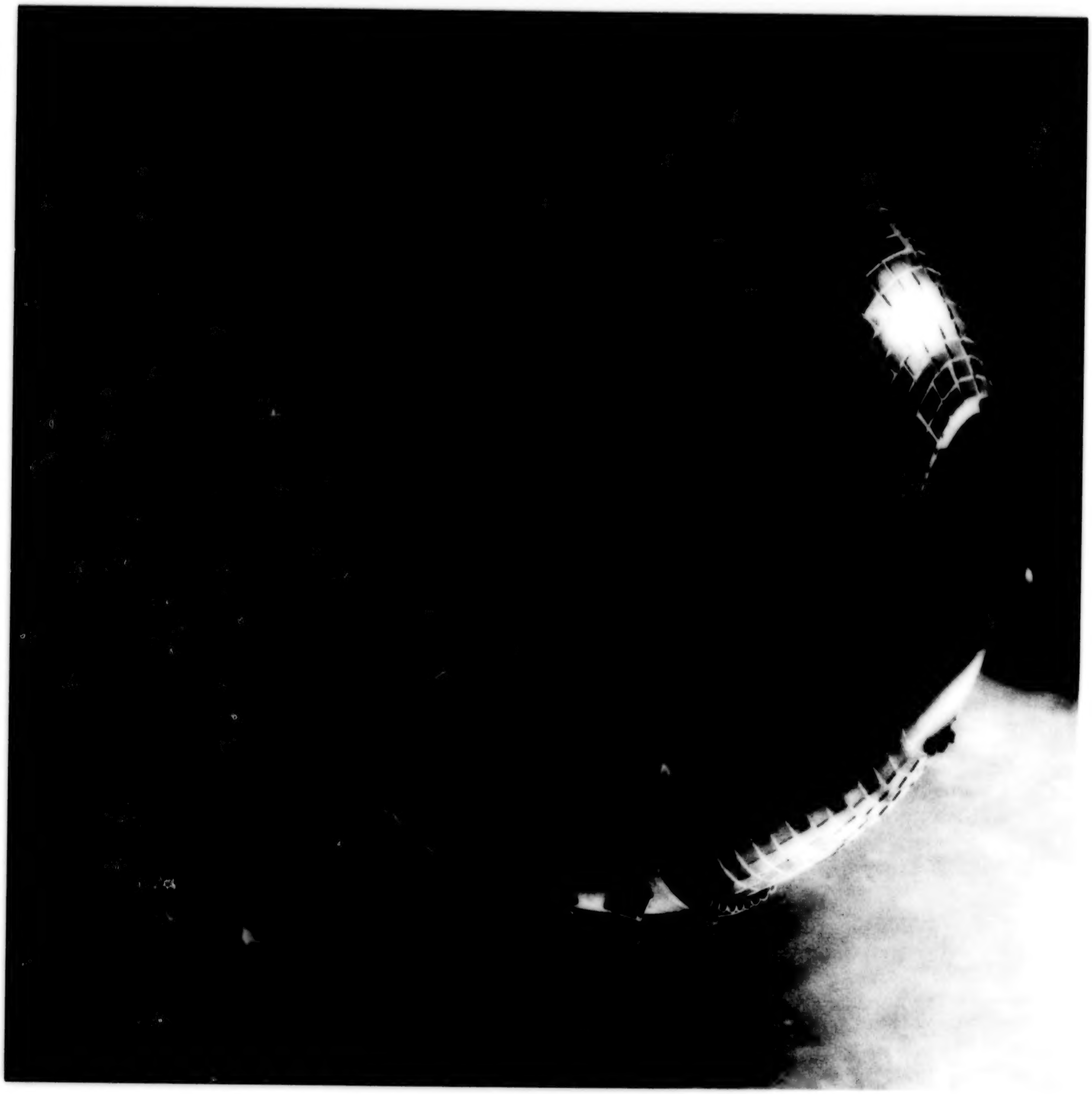

2

OBJECTIVES AND ORBITS

Although ground-based remote sounding of the upper atmosphere began in 1926, the study of the physics of the upper atmosphere–its composition and chemical reactions–did not move rapidly until sounding rockets were developed in the concluding phases of World War II. The first rocket soundings employed the V-2, which was developed in Germany and reconditioned in the United States. The study was later given a big boost by rockets developed by the United States, such as the Aerobees and Nike-Cajuns, that were designed specifically for probing the upper atmosphere. These activities took place during the 14 years before NASA was formed.

Atmospheric constituents were sampled directly in the years 1959 through 1964 through the use of a few rockets and satellites. In a 4-year period beginning in 1964, 147 sounding rockets were launched, mainly by NASA's Goddard Space Flight Center and various universities, to study the upper atmosphere. In the 10-year period that began in 1968, 187 aeronomy rockets were launched out of a grand total of 1154 sounding rocket launches.

Despite tremendous progress made by these sounding rockets in revealing information about Earth's upper atmosphere, such vehicles had severe limitations. Their measurements were made for only a short period of time as the rocket zoomed up and then fell back again. The measurements were local–vertically above the launching site. In addition, the payloads of these rockets were limited, and the instruments carried by each rocket had to be calibrated for each flight so that reduction of data from each flight was time-consuming. Satellites overcame some of these disadvantages. Sputnik III, the first Russian satellite for atmospheric experiments, provided information about ion composition, gas density, and ion density. An early American satellite, Explorer VIII, provided (through its ion energy measurements) the first direct confirmation of the presence of helium in the upper atmosphere. Measurements of diurnal variations of neutral particle density were made with an instrument carried by a Discoverer satellite, one of a series of military research satellites of the U.S. Air Force launched from the Western Test Range. Several satellites of this series returned data to Earth in capsules. Measurements showed four times greater atmospheric density at a given high altitude on the dayside of Earth as on the nightside. This confirmed earlier studies of satellite drag effects that suggested the Earth's atmosphere bulges into space on the sunlit side as a result of solar radiation heating.

FIRST AERONOMY SATELLITES

The first comprehensive aeronomy satellite was launched on April 2, 1963. Originally called an Atmospheric Structure Satellite (S-6), it was one of the Explorer series of satellites, and when successfully in orbit, it was designated "Explorer XVII." It later became known as Atmosphere Explorer A. The satellite carried

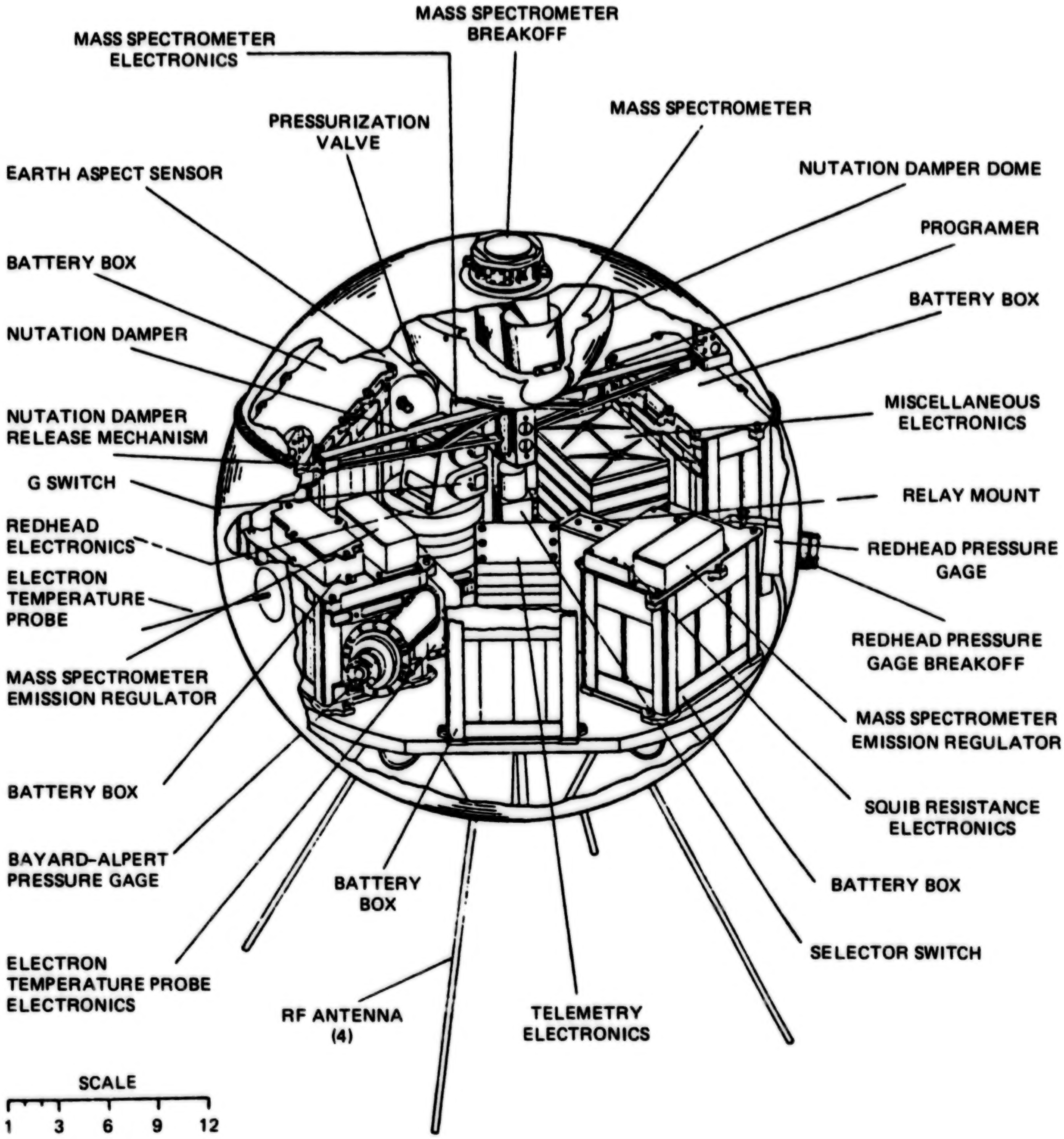

Figure 11. Cutaway view of the first Atmosphere Explorer showing internal components and science payload. This satellite had a limited operational lifetime because it did not carry any solar cells.

experiments for measuring the density, composition, pressure, and temperature of the atmosphere and the electron temperature at altitudes between 250 and 900 km.

The spacecraft (figure 11) was a spherical, approximately 1-meter diameter satellite weighing 184 kg. Its 0.6-mm thick stainless steel shell was designed to be nearly leak-proof to

prevent gases from the spacecraft from contaminating the tenuous atmosphere being sampled by the spacecraft's instruments.

Atmosphere Explorer A carried eight primary instruments: two mass spectrometers for sampling the neutral gas components, four vacuum gages for sampling the atmospheric pressure, and two electrostatic probes for measuring the temperature of electrons and the density of positive ions. A neutral gas mass spectrometer counts electrically neutral particles by breaking them into positive ions and negative electrons. The resulting charged particles are deflected by magnetic fields that sort the particles into different masses so that they can be counted. The instrument was needed in the Atmosphere Explorer to identify components of the atmospheric gases.

Electrostatic probes detect the flow of electrons and ions that result from the application of differing potentials to the cylindrical electrodes of the instrument.

The Atmosphere Explorer was launched from Florida by a Thor/Delta launch vehicle. The planned orbital inclination was 58 degrees from the Equator so that the satellite's coverage would extend to within several degrees of the Arctic and Antarctic regions. The actual orbit obtained was inclined 57.63 degrees, its period was 96.4 minutes, and the highest point was 963 km. When injected into orbit, the satellite was spin-stabilized at 1.5 revolutions per second, but there was no control over the spin axis, and it precessed about 10 degrees per day because of the interaction of the internal magnetic fields and the Earth's field. As a consequence, the satellite achieved optimum orientation for its science measurements only infrequently during its mission, thereby complicating data analysis. Orientation of the spin axis was referenced to the Sun, Earth, and Moon so that the experimenters could interpret the data gathered by the satellite's instruments.

Electrical energy was supplied within the spacecraft by silver-zinc chemical batteries weighing about 68 kg; the satellite did not carry solar cells. With all its instruments operating, the satellite consumed 100 watts of power and could operate at that rate for only 70 hours. Since the expected lifetime was 2 to 3 months in orbit, the satellite was turned on and off for operational periods lasting about 5 minutes only. Because data could not be stored on board the spacecraft, they had to be gathered in the range of the ground stations. To send the data to Earth, the satellite used a new pulse-code modulation telemetry system with an output power of 500 milliwatts that provided 40 channels. This was the first time the new system had been used in a spacecraft.

Before this satellite was launched, the scarcity of data on the neutral upper atmosphere was so great that scientists expected a mere 2 days in orbit would more than double the direct measurements made previously in the 250- to 900-km region. Nearly all the data that had been used to model the neutral upper atmosphere thus far had come from observations of the decay of satellite orbits. These observations provided only limited information, the interpretation of which required a number of assumptions, especially about composition.

The satellite continued to function until July 10, 1963, when its transmissions ended due to battery depletion. Its orbit finally decayed to a reentry and destruction of the silent satellite on November 24, 1966.

During its short lifetime, Atmosphere Explorer A not only demonstrated that satellites could be used to obtain uncontaminated measurements of the atmospheric composition but also made several important scientific discoveries. It discovered that the Earth is surrounded by a belt of neutral helium atoms, as drag effects on the Echo 1 satellite had implied. At the perigee

of its orbit, its instruments measured about 60 million helium atoms per cubic centimeter, whereas at the apogee or highest point (925 km above the Earth's surface), there were only one million helium atoms per cubic centimeter. The experimenters found that the neutral helium layer began about 97 km below the altitude where space researchers first measured an electrically charged belt of helium some 2 years earlier with sounding rocket probes P21 and P21A, which were launched during daytime and nighttime, respectively. The pressure gages carried by this first Atmosphere Explorer measured a perigee pressure of about one-hundredth of one-billionth that of the pressure at sea level and an atmospheric density of 2.7×10^{-8} grams per cubic centimeter.

Thousands of measurements showed that the temperature of the ionospheric electrons exceeds the temperature of the neutral atmosphere by a factor of 2 or 3 in the daytime above 200 km, but approaches the neutral gas temperature at night. These elevated electron temperatures were found to be caused by solar extreme ultraviolet radiation which produced photoelectrons that in turn shared their energy with ionospheric electrons. Typical daytime temperatures at middle latitudes were about 2200 and 1000 K at night. Higher nighttime electron temperatures were frequently found at high latitude, probably as the result of magnetospheric sources of heat.

Three years after Atmosphere Explorer A, another explorer (B) was launched (figure 12). Originally a backup for Explorer XVII, this spacecraft now became Explorer XXXII after its successful launching on May 25, 1966, by a Thor/Delta from Florida.

Like the first Atmosphere Explorer, the second spacecraft (figures 13 and 14) consisted of a hermetically sealed sphere of thin stainless steel carrying a turnstile antenna. Two electrostatic probes protruded 45.7 cm from the Equator of the spinning satellite. To extend its operational lifetime, Atmosphere Explorer B carried 2064 solar cells, bonded to the shell of the spacecraft. The expected operational lifetime was thereby extended to about 1 year by trickle-charging the batteries from the solar cells.

The primary scientific goal of this aeronomy satellite was to collect geographically extensive and accurate data to provide a better understanding of how and why changes occur in the upper atmosphere. A secondary objective was to study the effects of short-term disturbances in the atmosphere caused by radiation from solar storms. The satellite was launched when solar activity was building up to a maximum.

This second aeronomy spacecraft was more advanced than its predecessor in that it carried a tape recorder for storing information obtained over areas where there were no ground stations to record the data as they were gathered. In addition, the spin axis of this spacecraft could be controlled so that the spacecraft would have a near ideal orientation for taking measurements. As with the first Atmosphere Explorer, this spacecraft was designed and built by NASA/GSFC's Spacecraft Technology Division and the Aeronomy Branch.

To prevent buildup of internal pressure within the spacecraft due to gases that were generated by the internal batteries, the designers included three fuel cells that would convert the hydrogen and oxygen gases into water that could be stored within the spacecraft. Should this be inadequate, a valve in the spacecraft's shell could be commanded to release internal gases at a rate of about 3 pounds per square inch per day. However, this would be done only when the instruments were switched off and the gases could be jettisoned without interfering with the measurements of the gases in the upper atmosphere.

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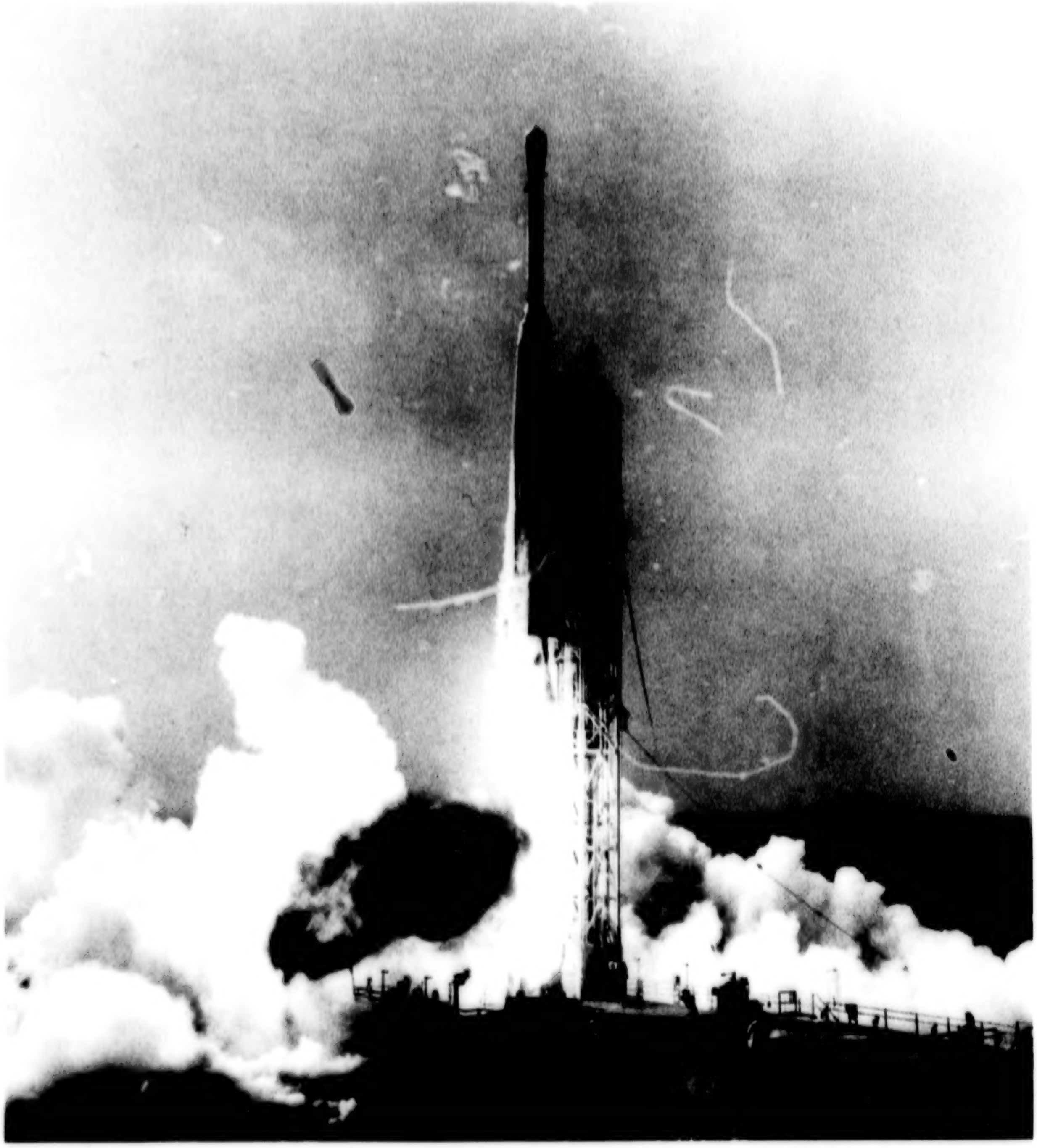

Figure 12. A second, more advanced Atmosphere Explorer satellite was launched in 1966.

The spacecraft was spin-stabilized, and used a yo-yo despin mechanism to attain the required rate of 30 revolutions per minute. The mechanism consisted of two long wires with weights at the ends that automatically unlatched in orbit and unwound from around the equator of the satellite. When the weights reached the full length of the wires, they were released, thereby carrying the required amount of angular momentum from the spacecraft.

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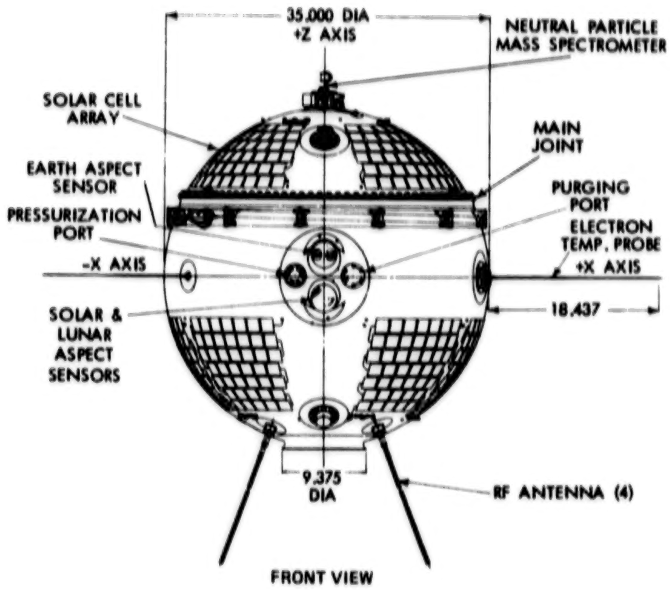

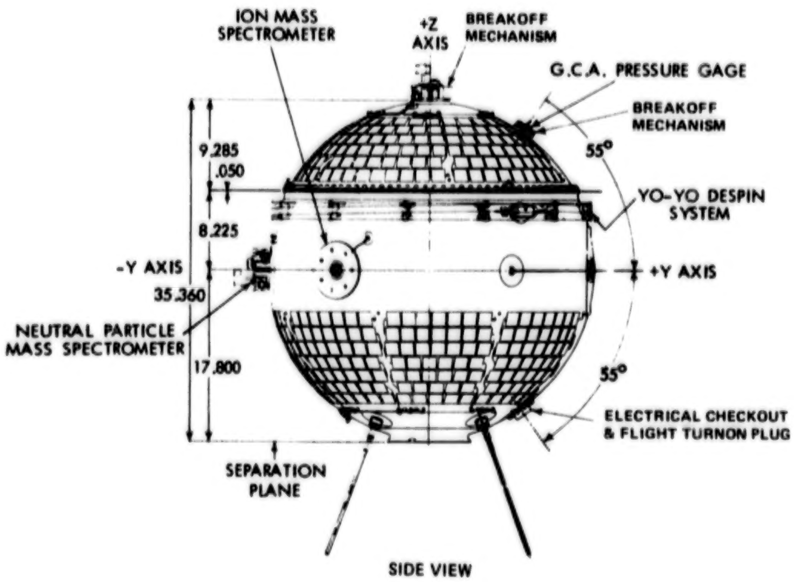

Figure 13. Atmosphere Explorer B showing the location of instruments and solar cells.

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Figure 14. A technician at the Goddard Space Flight Center attaches the Langmuir probe to the flight model of Atmosphere Explorer B.

The payload consisted of three groups of instruments. Nearly equally spaced around the equator of the satellite were a neutral-particle mass spectrometer, an ion mass spectrometer, two magnetron density gages, and two electrostatic probes. Fifty-five degrees toward the top pole of the spinning satellite was a magnetron density gage, and at the pole was a second neutral-particle mass spectrometer. The spacecraft's spin axis was oriented perpendicular to the orbit plane so that the gas samples were obtained first in the direction of satellite motion and then opposite to the forward motion after the spacecraft rotated through 180 degrees. This orientation greatly enhanced the capability to make measurements of the upper atmosphere by revealing the effects of the velocity of the spacecraft along its orbit.

The eight instruments were selected on the basis of the results obtained from the first aeronomy satellite. In particular, they were

designed to make high-resolution direct measurements of neutral and charged particle constituents of Earth's upper atmosphere, thereby collecting data for analyzing the distributions and concentrations of the particles and their energies. All the instruments were provided by scientists at the Goddard Space Flight Center.

A magnetic device was used to maintain the spin axis in a direction normal to the plane of the satellite's orbit. This device generated a magnetic dipole moment about the spacecraft and aligned along the spin axis. This moment reacted with the Earth's magnetic field to precess the spin axis at a rate of about 0.25 degrees per minute, which was sufficient to correct for deviations from the orbital plane.

The spin rate of Explorer B could also be changed at a rate of 15 revolutions per minute in 24 hours, by generating a magnetic dipole moment in the satellite's equatorial plane and phasing it with Earth's magnetic field. A digital Sun sensor and Sun slit provided measurements of the angle between the Sun and the spin axis of the spacecraft. The slit also provided a time pulse whenever it swept across the Sun, thus relating the spin position of the spacecraft relative to the Sun. Two sensors detected the horizon of the Earth, and a Moon sensor was used when the spacecraft was in Earth's shadow.

The satellite returned a large quantity of data over a period of approximately 6 months. The composition of the neutral atmosphere based on measurements made by Atmosphere Explorer B revealed the first *in situ* measurement of neutral hydrogen at orbital altitudes. Concentrations were higher than expected from most models of the upper atmosphere developed to that time (figure 15). Detection of hydrogen confirmed inferences made from measurements by instruments carried by other satellites. Atmosphere Explorer B also measured

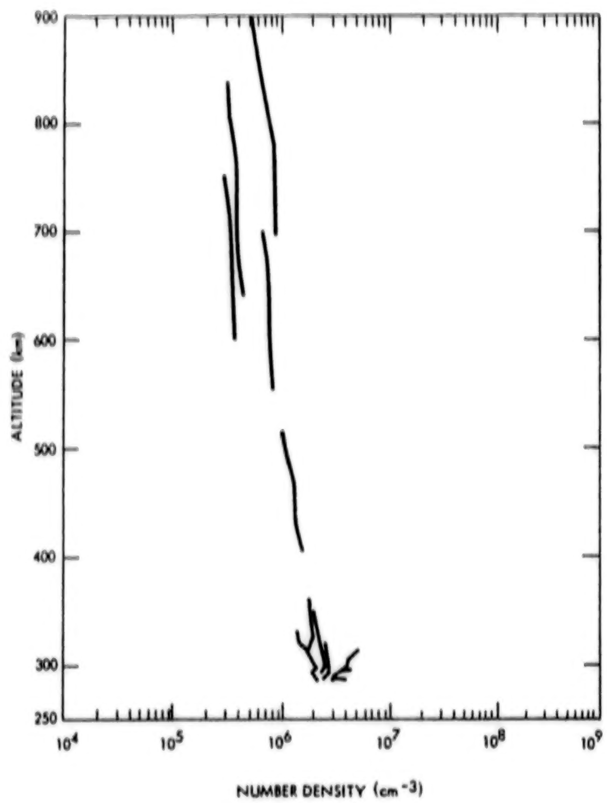


Figure 15. Atmosphere Explorer B made the first direct measurement of hydrogen in the thermosphere. This plot shows neutral hydrogen number density measured at various altitudes during May 1966.

number densities of helium, atomic oxygen, and molecular nitrogen.

By mapping electron temperatures in the ionosphere, the satellite provided a valuable supplement to the ionospheric electron temperatures obtained from ground-based observations with incoherent scatter radar at the Arecibo Ionospheric Observatory, which had been measuring variations with time of day.

Direct observations of wave motions in the neutral constituents of the thermosphere and the exosphere were measured and correlated

with similar wave structure in the electron concentrations, thereby demonstrating a dynamic nature of the upper atmosphere that had previously been unknown.

Experience with Atmosphere Explorer B confirmed the value of an orbit that essentially decoupled the altitudinal and local time motions of the orbit so as to separate altitude and local time structure of the thermosphere. The experimental results also showed that the behavior of the upper thermosphere is strongly governed by the lower thermosphere. Exploration of the lower region by a new class of satellites would be expected to produce information of great significance in atmospheric physics. Eventually, the Atmosphere Explorer B spacecraft lost internal pressure, presumably due to a meteorite. Shortly afterward, in December 1966, the signals from Atmosphere Explorer B ended because of battery electrolyte exhaustion.

NASA/GODDARD SPACE FLIGHT CENTER STUDIES

During the spring of 1965, Spacecraft, Incorporated, of Huntsville, Alabama, under contract to the Goddard Space Flight Center, began a small study to determine the propulsion needed to maintain in orbit a satellite that could dip deep into the thermosphere to continue the work begun with Atmosphere Explorers A and B but with capability of operating for a much longer mission. Such a spacecraft should be able to plunge repeatedly to an altitude of 130 km and regain its orbit. Using these results, RCA also did a somewhat similar study that resulted in an unsolicited proposal for a low-altitude satellite spacecraft. The teams at NASA/GSFC who had spearheaded the investigation of the thermosphere with Atmosphere Explorers A and B provided some support funding to these organizations to supplement their own investment of research and development funds. The result was the development of a concept for a spacecraft that would contain a propulsion system. This concept was called a Variable Orbit Scientific Satellite, referred to at that time by the acronym "VOSS." At GSFC, James Walker, Larry Brace, and Nelson Spencer defined the initial science goals for the new spacecraft, and a science working group was formed from university researchers and the small group of upper atmosphere physicists at NASA/GSFC who had dedicated their professional careers to upper atmosphere research.

The science working group continued feasibility studies for the VOSS and pushed their ideas strongly in the right places. They helped evolve the concept for the spacecraft, and they defined the measurements that should be made. As a result, the concept for the next satellite in the Atmosphere Explorer series was for a 454-kg spacecraft with 90 to 136 kg of scientific instruments and up to 180 kg of propellant. Its payload of science instruments and the repeatedly attainable low perigee would permit, for the first time, measuring the photochemical and thermal theory of the upper atmosphere. The preferred orbit was highly elliptical so that the spacecraft could dip deep into the atmosphere.

Additional research would benefit from a circular orbit. Thus, with propellant on board the spacecraft, initial concepts for its mission considered permitting the elliptical orbit to decay to a circular orbit at an altitude that could be maintained through the use of the propellant.

Experience with the A and B spacecraft had demonstrated that the spacecraft should be stabilized and, to reduce drag effects, the spacecraft must have a low area-to-mass ratio. The concept evolved was that of a short right-circular cylinder with good stiffness so that it would not torque under aerodynamic imbalance that would be experienced because the exact

position of the center of pressure could not be defined. The concept of a large momentum wheel was evolved. A momentum wheel inside the spacecraft spun on the central axis. A mirror at the bottom of the spacecraft, but attached to the wheel, scanned the Earth. The spinning wheel permitted the main body to be despun, making possible the stabilized mode of operation. The center section, which consisted of two baseplates 43 cm apart, contained the propellant tanks. Equipment was mounted on either side of the center section on the baseplate. The design was the result of a joint effort by NASA/GSFC and RCA.

The science team also investigated the instruments that could be carried by such a spacecraft with the capability of dipping into the atmosphere to as low as 125 to 130 km, below the altitude at which most of the energy from incoming solar ultraviolet and X-ray radiation is transferred into the atmosphere. Scientific objectives for the new spacecraft also required measuring extreme ultraviolet radiation from the Sun, the number densities and temperatures of neutral particles, ions, and electrons, the spectrum of photoelectrons, and the airglow at selected wavelengths.

By April 1967, a plan has been selected for both the spacecraft and the experiments. A report authored by D. W. Grimes, W. D. Hoggard, L. H. Brace, J. C. C. Walker, and N. W. Spencer, of Goddard Space Flight Center, documented a feasibility study for two new Atmosphere Explorers. Several spacecraft systems had been considered as candidates for the low-perigee mission, including the Orbiting Solar Observatory spacecraft, Percheron, Tiros-K, Tiros-M, and a modified Atmosphere Explorer B. Of all these systems, Tiros-M most nearly met the objective. One disadvantage of the Tiros-M was its lack of a suitable aerodynamic shape for minimizing drag during the perigee passages. However, RCA had performed an in-house study that resulted in the definition of a Tiros-K′ spacecraft—a Tiros-K with a despin mechanism—that was a near-optimum aerodynamic configuration for the Atmosphere Explorer task.

The new Atmosphere Explorer mission was a natural extension of the earlier missions, but the improvements in onboard propulsion and other technologies permitted extending exploration into the lower thermosphere where the solar ultraviolet radiation is absorbed and the energy and chemical balance of the thermosphere is determined. This region had often been referred to as the "ignorosphere" because there was so little information about it and its investigation had been largely ignored during the expansion of scientific experiments farther and farther into space by satellite.

Atmosphere Explorer B permitted mainly studies of the atmosphere's diurnal variations. In their lower perigee orbits, the new satellites would permit studies of the altitudinal structure of the thermosphere. A further improvement expected by the mission planners was the expansion in scope of the investigation, mainly by adding measurements of the ultraviolet energy input to the atmosphere and certain airglow emissions. These new observations were needed to determine the rates at which important excitation and ionization processes occur in the thermosphere.

Thus, at this time, the emerging technical plan called for modifying a basic Tiros spacecraft design to accommodate the experiments and other mission-oriented subsystems. It required a continuous power of 10 to 30 watts for the experiments and a data storage capacity of 31 million bits of information. The science payload and spacecraft subsystems were to be mounted on both sides of a standard Tiros baseplate and enclosed on the top by a multisided shell sectioned like a hat and covered

with solar cells. The bottom of the spacecraft was enclosed by a glass-covered cylindrical aerodynamic skirt that was configured to minimize aerodynamic drag and torquing. A magnetic moment control subsystem, similar to the one used on the Tiros and TOS spacecraft, and a momentum wheel subsystem then under development for the Tiros-M spacecraft would provide attitude control. The spacecraft would have two modes of operation in orbit. In the first mode, the spacecraft would spin at four revolutions per minute with the spin axis perpendicular to the plane of the orbit. In the second mode, the spacecraft would spin at one revolution per orbit with a fixed orientation to the Earth and with the spin axis also perpendicular to the plane of the orbit.

Hydrazine monopropellant thrusters had been developed, and five of them were proposed for the spacecraft. Adjustments to the velocity would be made during the despun mode of operation of the spacecraft. These adjustments would be made by firing a 5-lbf thruster at apogee (to change perigee height). The other four thrusters each developed only 0.1 lbf and were used to correct disturbances to the system, such as precession of the spin axis, and for small angular momentum changes. A liquid nutation damper and a magnetic attitude control system would fine-tune the orientation of the spacecraft.

A 227-kg spacecraft needed approximately 0.45 kg of propellant to change the perigee by 15 km. Initial planning anticipated that the total of all changes to the perigee might add up to 359 km, which would require the expenditure of 10.9 kg of propellant. To accomplish the scientific objectives of the Atmosphere Explorer mission, eight instruments were originally planned. These were an ion mass spectrometer, a cylindrical electrostatic probe, a retarding potential analyzer, a photoelectron detector, an extreme ultraviolet photometer, two neutral mass spectrometers, and an airglow photometer.

The plan included a major change from earlier space missions in handling the data, which were to be made available quickly and shared among the different participants, both experimenters and theorists.

With the plan developed, the NASA/GSFC team then proceeded to the long process of presenting it to various committees for their support of the mission. Presentations were made to show the VOSS concept as applied to the science platform with the capability of spinning or despun operation and onboard propulsion.

When the plan had received the blessing of peer science groups, it was further refined and then proposed to NASA Headquarters for becoming an active and funded program.

By 1970, on a basis of open competition, a larger team had been assembled by NASA Headquarters, which consisted of 17 scientists. This team included scientists from NASA/GSFC and from many universities and other science institutions. At this time, a carefully coordinated team approach to conduct the mission had been outlined, the members of which included both theorists and experimenters who had joined together to use the proposed Atmosphere Explorer satellites to mount a concerted attack on the many physical problems of the thermosphere.

At several meetings over the preceding 3 years, the original science team accomplished several important goals essential to initiating a new space project. They helped the Atmosphere Explorer project define the spacecraft system, with special attention to the relationship of scientific objectives to the selection of orbit and the design of the spacecraft. They defined and described the outstanding atmospheric problems and determined how the Atmosphere Explorer satellites could best be employed to

solve these problems. Finally, they established a workable relationship within which theorists and experimenters could combine their thinking efforts to plan the mission, define the experiments, guide the effort of data reduction, complete the interpretation of data, and publish the scientific findings from the mission.

The working arrangement that evolved rested on the concept that the acquisition, reduction, and interpretation of data should not be separate functions, but should be combined to provide an interchange of information and ideas between these functions. More specifically, each member of the team devoted his efforts to two or more study groups, each of which had as its goal the solution of one particularly well-defined atmospheric problem. Examples of such problems were also defined. They included the question of the ion and neutral composition of the atmosphere and the reaction rates among atmospheric components, the energetics of the ionized atmosphere, the processes that control the low-energy electron spectra, the processes responsible for the excitation of the airglow, and the global structure and dynamics of the neutral atmosphere.

An early task of each group involved defining, before launch, the specific measurements required for the group's study—what should be measured, where, when, and how often. During the active life of each satellite, each group was also expected to review periodically some of the current data so that the data acquisition plan could be changed as needed to take advantage of the information gained to that point in the mission. The study groups also established priorities for reducing and analyzing the data.

By August 1969, the various instruments to be carried by the spacecraft were clearly defined. These instruments are described in a subsequent chapter. The mission plan for the first of the satellites had also been further clarified. It was proposed that the mission should consist of two phases. In the first phase, the spacecraft would move in an eccentric orbit so that measurements could be obtained over a wide range of altitudes. For the operational phase, the satellite would be placed in a circular orbit to investigate the global structure of the atmosphere at each of several fixed altitudes.

The plan not only provided details for each aspect of the operational mission, but also gave the rationale behind all the proposed instruments and estimated their costs.

CONTRACT AWARDS

In December 1969, after a competitive selective bidding process, NASA selected both Hughes Aircraft Company Space Systems Division and RCA/Astro Electronics Division to receive parallel 4-month, $250,000 fixed-price study contracts for defining and designing the Atmosphere Explorer satellites. The Atmosphere Explorer project was funded as an official project in 1970, for the launch of Atmosphere Explorer C in 1973, Atmosphere Explorer D in 1974, and Atmosphere Explorer E in 1975.

At the conclusion of these contracts, a further competition was run between these two companies, and in March 1971, RCA/Astro Electronics Division was selected to conduct the spacecraft effort and build the three spacecraft at an initial estimated cost of $12 million.

The spacecraft contract was for the final hardware design, development, fabrication, integration, test, launch support services, and orbit operation support for the three spacecraft. Associated spares and ground equipment were also to be supplied under the contract.

A Space/Experiment Interface Definition Study was contracted to RCA separately from the

prime spacecraft hardware contract to ensure that the experimenters had sufficient interface data to enable them to design their instruments at an early stage.

In November 1972, NASA announced the selection of Xerox Data Systems for contract negotiations to provide the central data handling facility and remote terminals for the Atmosphere Explorer program. A contract was awarded following these negotiations. The central computer concept was unique to the Atmosphere Explorer project and was designed for maximum interplay of scientific data between the experimenters. This concept also eliminated the requirement for each scientist to reduce his own data.

The Thor/Delta launch vehicles were procured from McDonnell Douglas Aircraft Company.

THE ATMOSPHERE EXPLORER ORGANIZATION

The Atmosphere Explorer program (see Appendix A) was directed from NASA Headquarters, Office of Space Science and Applications, by Frank W. Gaetano, with Dr. E. R. Schmerling as program scientist. The project was managed by NASA/GSFC. The project manager was David W. Grimes, and his assistant was E. Dale Nelsen. The project scientist was Nelson W. Spencer, the project coordinator was William D. Hoggard, and the spacecraft manager was Robert C. Weaver. David J. Haykin served as mission operations director, and R. Donnelly acted as payload manager.

Several review teams were established to ensure that the Atmosphere Explorer met all the requirements for the engineering and scientific objectives of the missions. A Spacecraft Review Team reviewed the status of the spacecraft hardware, evaluating the efforts of the project team at the Goddard Space Flight Center and those of the spacecraft contractor. Members of the team attended the design reviews presented by the contractor and finally certified the adequacy of the spacecraft to perform its mission.

A Flight Readiness Review Team checked the readiness of the launch vehicle, ground-support equipment, launch complex, and launch support from the standpoints of hardware, software, and operational readiness.

An Aeronomy Team was formed from the 17 approved investigators, including the three theorists. The team reviewed all aspects of each flight, recommended specific mission parameters for all flights, recommended additional measurements as required, performed in adaptive mission planning during the flights, and ensured the timely exchange and correlation of data and information so that the greatest scientific return could be obtained from each flight. The project scientist was permanent chairman of this team, aided by Alex Dalgarno and then William B. Hanson as cochairmen.

Project coordination meetings were held as needed to resolve interface problems in the various subsystems.

A Malfunction Report Review Team reviewed any malfunction to determine its cause and to approve corrective action. An Environmental Test Committee reviewed any changes from the environmental test plan. An Experimenters' Working Group, consisting of the project manager, project scientist, all the scientists, experiments manager, and NASA support personnel, resolved questions concerning spacecraft and experiment schedules, data analysis plans, test sequences, technical detailing for experiments, interfaces, and ground-support equipment, and data processing.

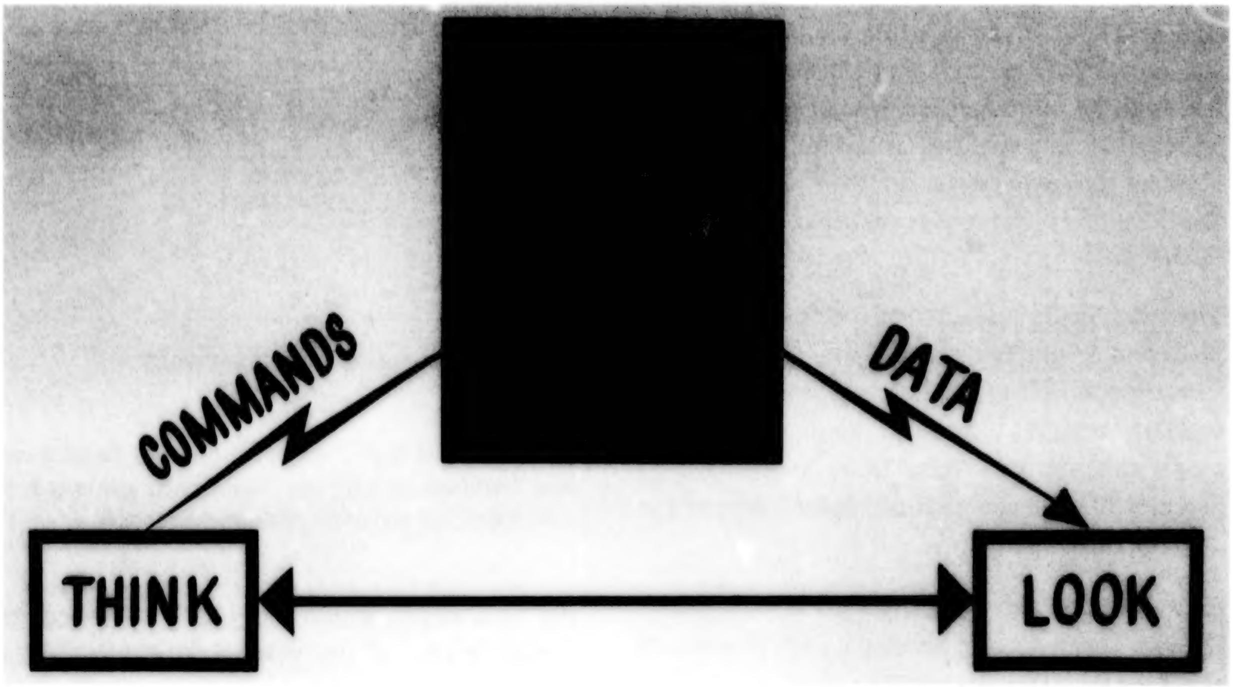
A Configuration Control Board, chaired by the project manager, considered the coordination and impact of proposed engineering changes and their effect on performance, schedules, cost, manpower, and reliability.

A major new concept in the program involved the team of investigators and the idea of sharing data. In the past, it often took months to ship data tapes from one machine to another for processing, and it took a long time for the data to become available to the scientists. Innovative changes in the traditional way of doing things provided the Atmosphere Explorer project with a centralized data system that allowed all the investigators to work more effectively and more efficiently. This data system innovation was later applied to other Earth science and planetary programs.

In most earlier projects, each scientist had exclusive rights to his data, and he did not release these data until he had analyzed and interpreted them. This procedure usually caused a long delay in making space data available to other scientists. The logical next step was to involve collaborative work in which expertise would be put together from different fields to interpret the results in the total import to the problems being attacked by the space mission. The accent moved from attempting to make better and better measurements of certain parameters to relating the measurements of one parameter to those of several other parameters. For example, how could the concentration of ionized oxygen atoms be related to the chemical reactions, the incoming ultraviolet radiation, and the background neutral atmosphere? For such cause and effect studies, it was necessary to change the traditional methods of operation and institute strong teamwork.

It became a team in the real sense because one investigator was trusted to measure a given parameter, such as the incoming ultraviolet radiation, and the other team members accepted his measurements. Thus, each expert made the fundamental measurements, while the team as a whole interpreted these measurements in the broad context of understanding the upper atmosphere. Therefore, the team had to include first people who had special knowledge and experience in making measurements in the thermosphere and then people who had a knack of tieing the entire thing together.

Immediately, a natural psychological problem arose in that the people who tie the measurements together, whom we might call theorists, might in effect take away the fruits of the work of the measurers, whom we might call the experimenters. It required quite an effort of program and project managers to encourage everyone to work harmoniously together rather than doing their own thing in their own areas of speciality. It worked. The team achieved a true unity, cooperating effectively in reaping the scopious new science the spacecraft afforded. The cartoon (figure 16) portraying the team suggests the unity achieved. This system proved that individuals could still make discoveries while working on such a team. The key to the entire operation was making data available quickly. It was soon realized that a net gain occurred when a worker gave up exclusive rights to one data set in return for access to twelve others. Before the new concept accepted for the Atmosphere Explorers became operational, it often took 6 months for data to become available through the system. Atmosphere Explorer broke into new territory by making data available not only quickly, but also to all the participants who wanted to use it, even before it had been processed and analyzed by any one individual. The team members helped tremendously to make this possible by realizing that they were not really giving their data away but rather exchanging



- **SEVENTEEN PI'S LINKED TO THE CENTRAL SIGMA 9 COMPUTER**
- **SPACECRAFT SCIENCE OPERATIONS COORDINATED THROUGH THE SIGMA 9 COMPUTER**
- **DATA PROCESSED IN THE SIGMA 9 COMPUTER UNDER PI CONTROL**
- **ONE TO 10 DAYS FROM COMMAND GENERATION TO PROCESSED DATA**
- **ALL DATA AVAILABLE THROUGH TERMINALS TO ALL PI'S**

Figure 17. The Atmosphere Explorer program used a new concept of handling data so that information from the science instruments would be available quickly to allow an adaptive mission and correlative research.

them for a much broader selection of data that enhanced the value of their own data. It became apparent that there would be much more data then any single person could handle.

The Atmosphere Explorer system provided access to data much more effectively than actually moving data tapes from place to place (figure 17). It made possible for the first time real correlative research that allowed test hypotheses to be put together. One of the essentials of scientific investigation is not only to provide a means for experts to do their job well, but also to allow many other people to have access to the data.

The most readily accessible forms of data were placed in a "unified abstract file." All principal investigators (PI's) had access to these data through remote terminals. If anyone needed more detailed data than those in the unified abstract file, special requests were made to the appropriate investigator.

A ground rule for the program was to operate the spacecraft 4 to 5 hours per day, process all the data that the spacecraft gathered, and put this amount of data in the unified abstract file. The overall system worked well, and data were quickly transmitted. On special occasions, an investigator with a terminal actually had access in his own office to data that had been acquired in space only 6 hours earlier (figure 18). Before Atmosphere Explorer, it often took 8 to 9 months to gain access to such data.

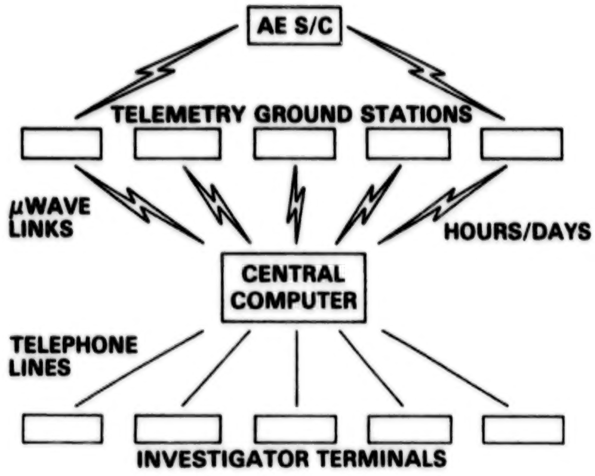


Figure 18. Through a central computer, investigators used terminals at their own facilities to gain access to both their own and other experimenters' data.

ORBITS

The primary scientific objectives of the mission could be best achieved by satellites in three different orbits of intermediate, high, and low inclination to allow selected coverage. A high ellipticity emphasized resolution in vertical profiles of the orbit, as well as permitting long lifetimes in orbit despite the low perigee. The stored kinetic energy of the highly elliptical orbit assisted in extending the lifetime of the satellite.

As mentioned earlier, the mission plan for the new Atmosphere Explorer was for two phases of operations. In the first phase, the orbit of the spacecraft would be highly elliptical to enable study of the vertical structure of the thermosphere. In the second phase, the orbit would be nearly circular, and this circular orbit would be placed at several fixed altitudes to investigate global structure of the thermosphere.

At the beginning of the first operational phase, the first satellite (Atmosphere Explorer C) was to be placed in an orbit with an intermediate inclination (68 degrees) to the Earth's Equator. The perigee was to be near 150 km and the apogee near 4000 km, and the orbit was to be maintained near these levels for approximately 8 months (figure 19). During these months, the orbit would itself move around the Earth with the perigee moving very slowly, allowing measurements at particular altitudes at a variety of local times. Occasionally, the propulsion system would be used to assist the apsidal rotation.

Also during this period, the perigee would be lowered to 130 to 135 km for brief excursions into the lower region of the thermosphere.

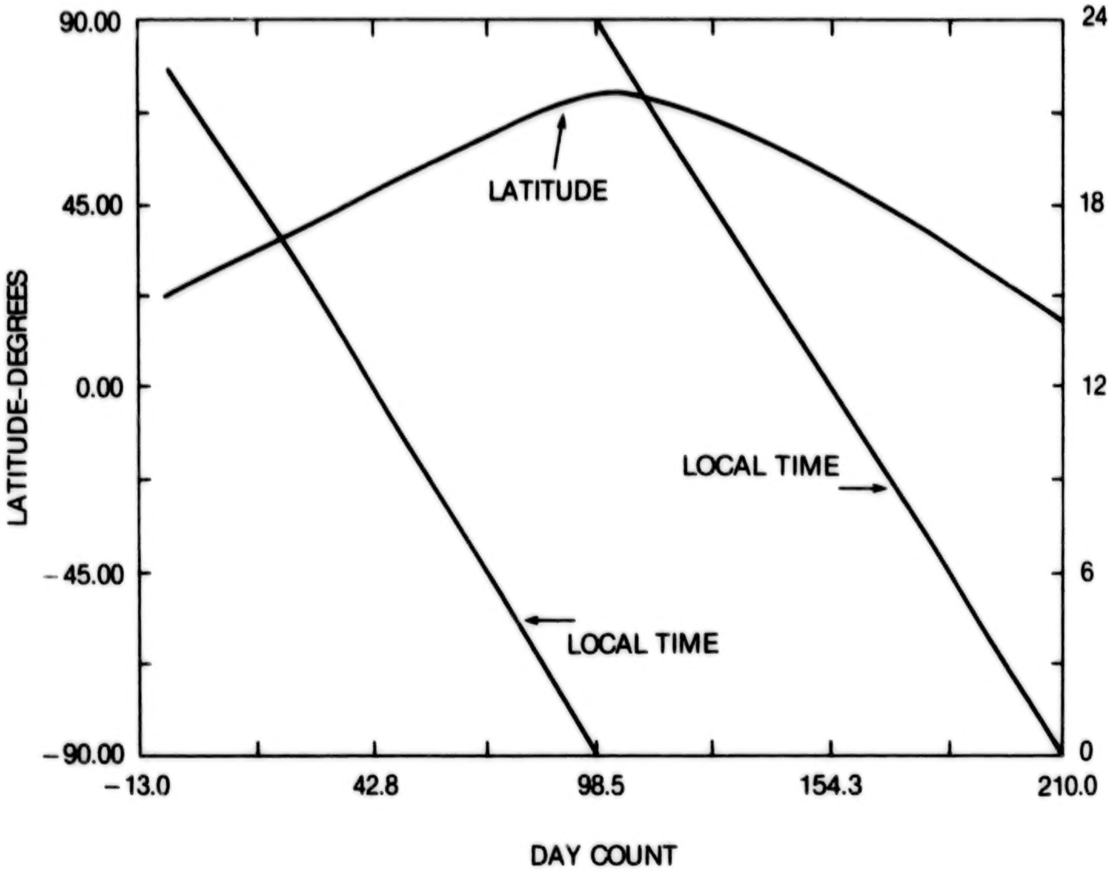


Figure 19. This plot shows the latitude and local time of the perigee of an Atmosphere Explorer over a period of 224 days from launch. The movement of the perigee allowed the satellite to explore the thermosphere at many times and places.

This would provide, for the first time, information on the behavior of the lower thermosphere and E-region of the ionosphere with suitable spatial and temporal resolution.

During the second operational phase, circular orbits of altitudes between 600 and 250 km were needed. At the end of the first phase in elliptical orbit, therefore, the altitude of the perigee was to be reduced to the lowest useful value—about 129 km. The resultant increase in drag would lower the apogee of the orbit. When it had decayed to 600 km, the propulsion system would be fired at apogee to raise the perigee, lower the apogee, and make the orbit circular. The satellite would then be kept in the circular orbit indefinitely, gathering data at all points along the orbit.

The propulsion system carried by each Atmosphere Explorer spacecraft permitted it to achieve orbits quite close to a true circle, so that only irregularities in the shape of the Earth produced significant changes in the altitude of the satellite as it orbited the Earth. The resulting increased accuracy of measurement of global pressure gradients could lead to more realistic calculations of the system of global winds in the upper atmosphere.

Before all the propellant was exhausted, the spacecraft would be placed in a suitably positioned circular orbit so that it would decay

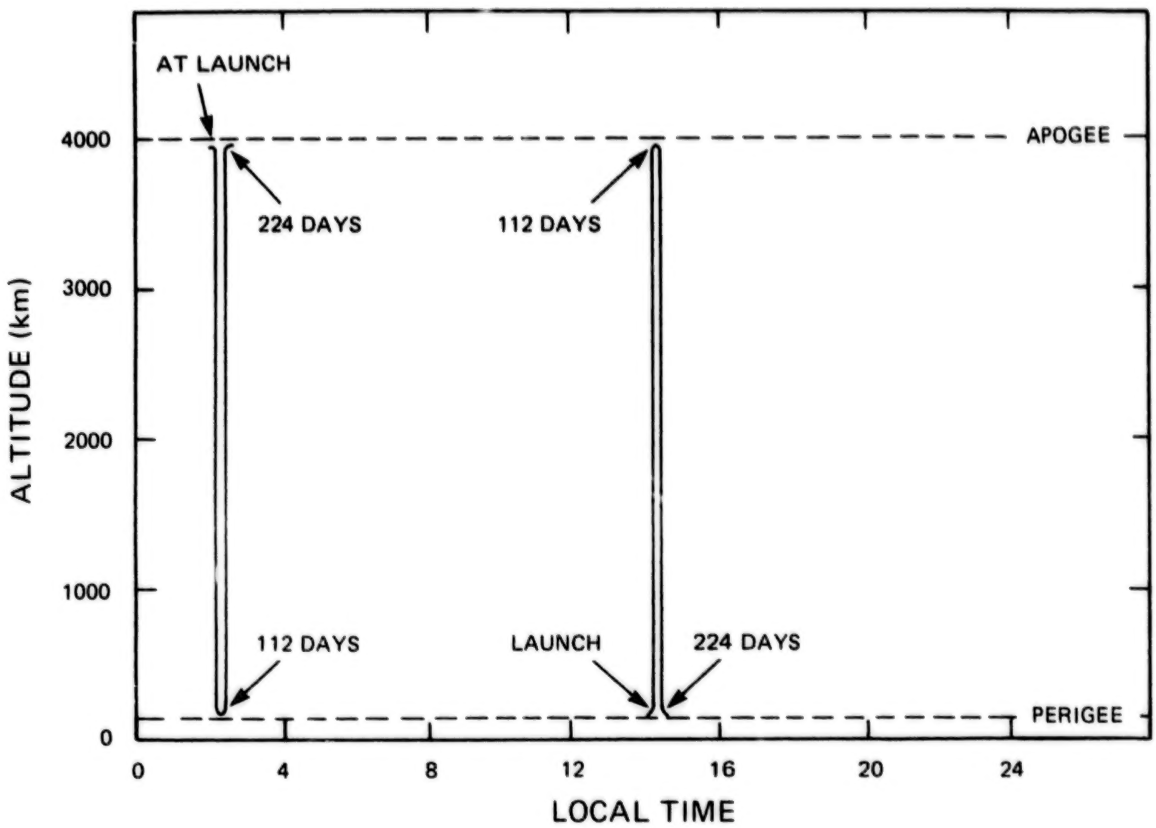


Figure 20. The apsidal motion of the orbit permitted the satellite to make measurements over a wide range of altitudes at each location, as shown in this diagram.

slowly—an orbit from which further observations could be made until the satellite could no longer be used.

The fixed altitude, global resolution provided during the second phase of operations permitted almost instantaneous resolution of global features such as the winter helium bulge and the latitudinal neutral density distribution.

Measurements of the changes in the vertical structure of the atmosphere are important. Such altitude profiles are vital to our understanding of the distributions of neutral particles and their temperatures, which are not locally controlled as are the temperatures of charged particles. The elliptical orbit selected for the Atmosphere Explorer mission permitted vertical profiles to be derived in two ways: (1) by the long-term changes in satellite altitudes at each measurement location, caused by the apsidal motion (figure 20), and (2) by the variations in altitude along the elliptical orbit path (figure 21).

The long-term altitude changes were derived from sequences of daily measurements at given locations that reflect primarily the vertical structure because altitude was the only structural coordinate that was changing. Day-to-day changes were caused by magnetic disturbances, solar flares, and other transient phenomena, and the manner in which data from these changes deviated from the main body of data identified these effects.

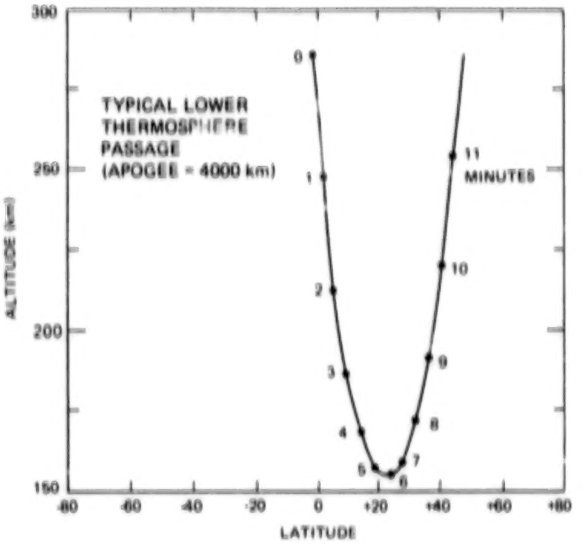


Figure 21. The path of the satellite near each perigee passage permitted it to make short-term measurements at various altitudes, as shown in this diagram. This figure demonstrates the degree to which the eccentric orbit emphasizes the altitudinal changes within each orbit.

Long-term variations of the atmosphere were expected to be superimposed on the altitude profiles. For example, a known 27-day cycle of neutral density was expected to appear three times on each full altitude sweep of 150 to 4000 km that took place over a period of about 3-½ months. Because each location permitted observation of a particular atmospheric characteristic at a different altitude, it was possible for scientists to derive the atmospheric response at all altitudes. Seasonal variations having a time scale comparable with the time for altitude sweeps (3-½ months) were identified by comparing the consecutive sweeps at each location.

The short-term altitude profiles obtained were of greatest use when the vertical gradients of most parameters being measured greatly exceeded the corresponding horizontal gradients encountered along the orbital path. On a typical orbit, the lower thermosphere was traversed twice in only 49 degrees of latitude. Excellent relative accuracy of the neutral measurements was expected to permit the detection of horizontal differences as small as a few percent by comparison of the downward and upward legs of each perigee passage.

The primary difference between the high inclination orbit for D and the intermediate inclination orbit for C was important to aeronomy because the motion of the perigee of D would translate into latitude coverage of the thermosphere, whereas that of C would give good local time coverage because of the slow motion of perigee.

The Atmosphere Explorer D orbit would be circularized similar to the Atmosphere Explorer C orbit and would be stepped through a similar altitude range. A pair of satellite orbits for studying global and local time behavior of the thermosphere was of great value. Similarly, Atmosphere Explorer E made possible a complementary low-inclination orbit mission for extensive equatorial investigations. Its inclination corresponded to the latitude of the Arecibo, Puerto Rico, incoherent backscatter station, permitting extensive correlative studies.

In summary, the Atmosphere Explorer C spacecraft was launched in 1973 by the improved Thor/Delta 1900 launch vehicle (figure 22). The orbit of the satellite was inclined at 68 degrees. Atmosphere Explorer D was launched in 1975 by a Thor/Delta 2910 launch vehicle (figure 23). Its orbit was inclined at 90 degrees. Both of these satellites were launched from the Western Test Range. Atmosphere Explorer E was launched in 1975 by a Thor/Delta 2910 launch vehicle from the Eastern Test Range. Its orbit was inclined at 19.7 degrees. All three satellites were intended to be placed in initial orbits with perigees near 150 km and apogees of 3000 to 4000 km. Mission profiles were determined by the aeronomy teams to meet the science objectives.

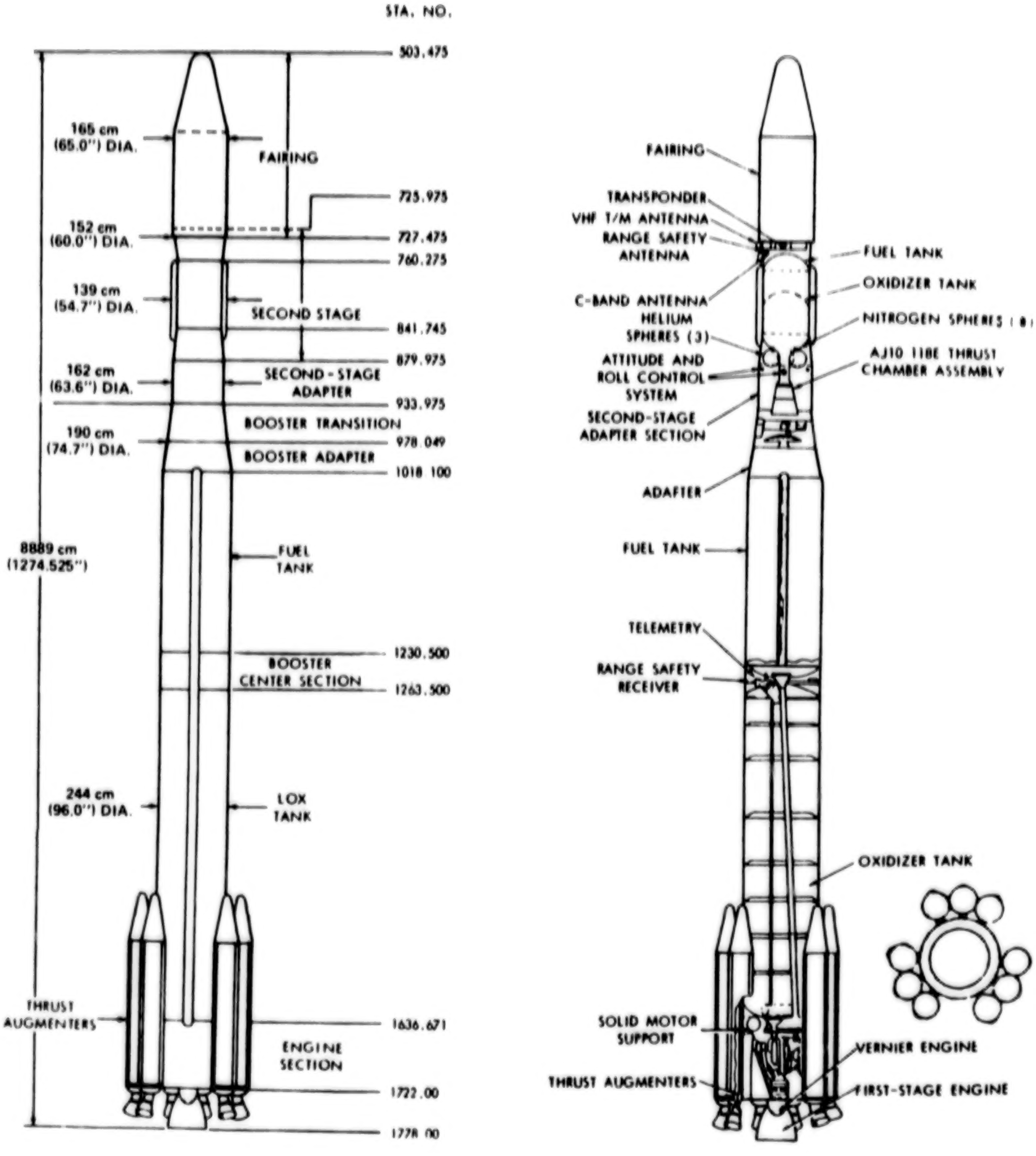


Figure 22. A Thor/Delta 1900 launch vehicle launched Atmosphere Explorer C.

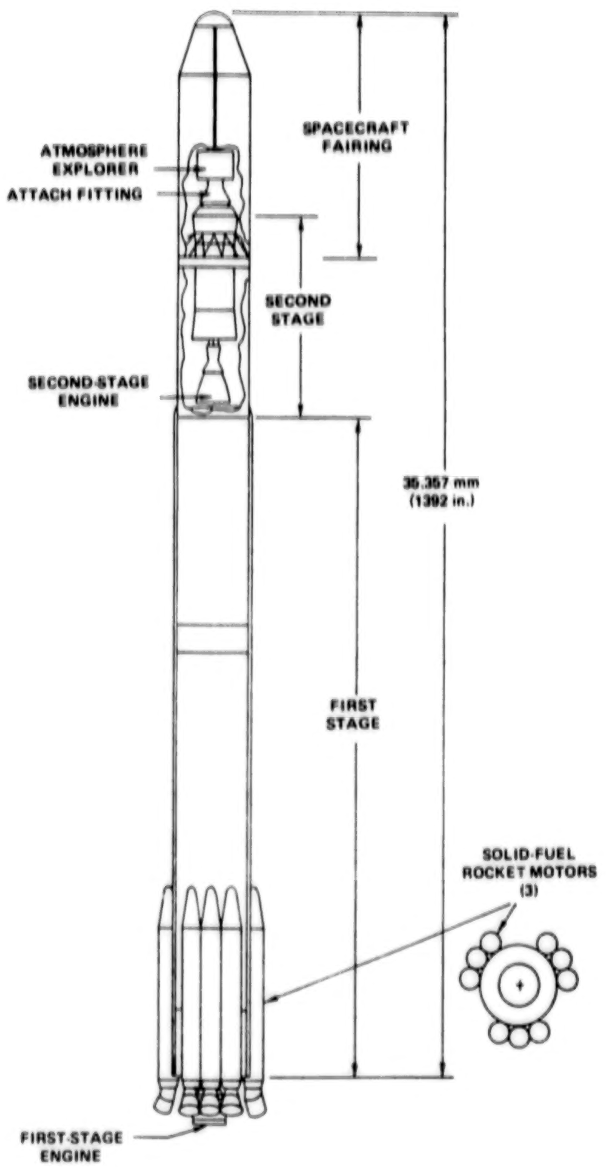


Figure 23. Thor/Delta 2910 launch vehicles were used to launch Atmosphere Explorers D and E.

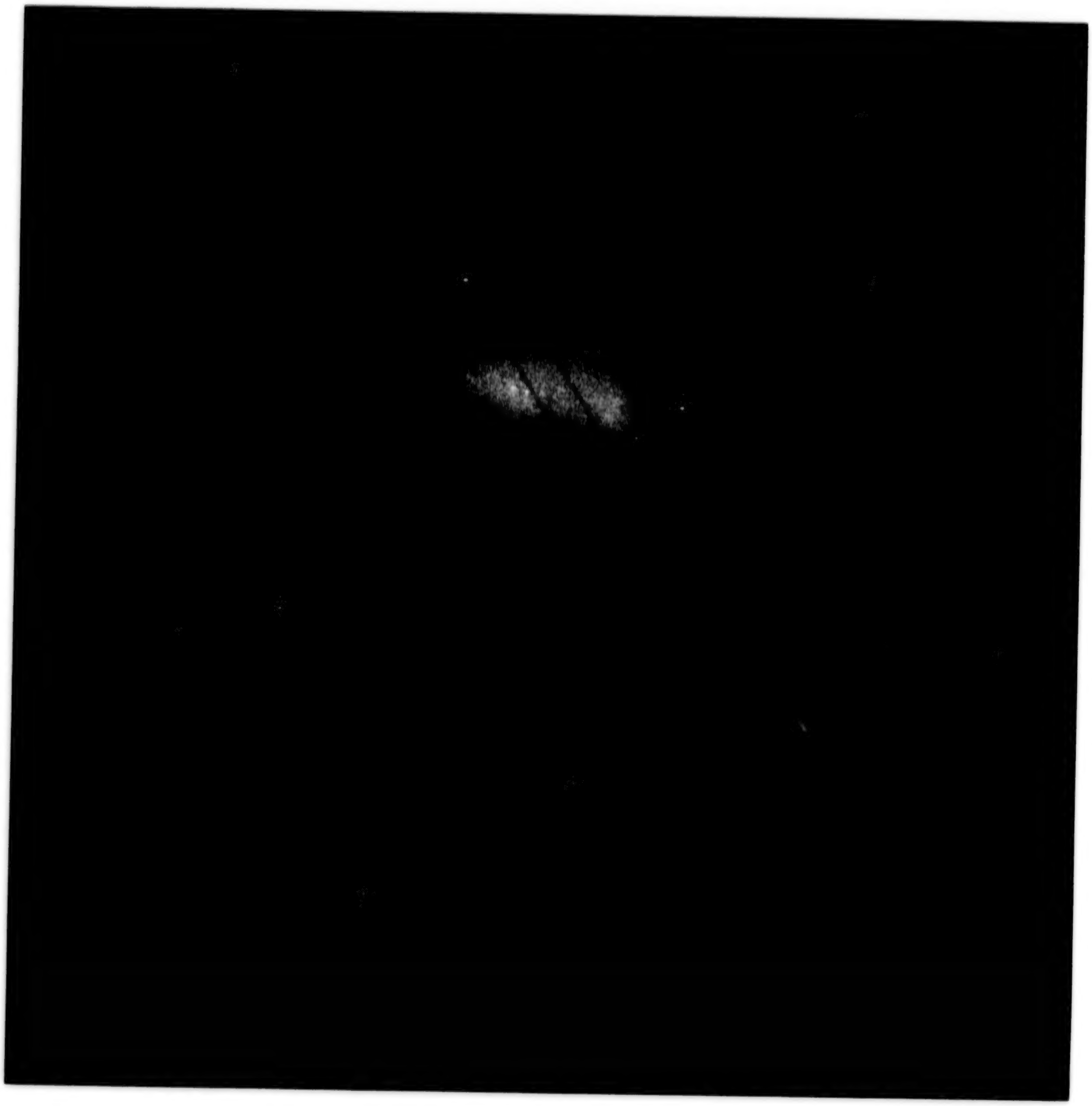
MISSION SCIENCE OBJECTIVES

The mission objective of the Atmosphere Explorer series was to investigate all aspects of the photochemical processes that accompany the absorption of solar ultraviolet radiation in the Earth's atmosphere by making closely coordinated and varied measurements of the reacting constituents from a spacecraft with onboard propulsion that permitted variations in perigee and apogee altitudes. In addition, this first mission permitted the development of the coordinated team approach to the study of the extremely complex aeronomic problems that the three missions were to address and exercised the low-perigee capability of the spacecraft system, the instruments, the ground support, and data systems to prepare for close coordination between the three missions.

Variations were expected over the ranges of latitude, local time, and season. Atmosphere Explorer C provided a stable perigee location and a constancy of altitude at various locations. It acted as a prototype to cover measurements over a range of altitude. Atmosphere Explorer D permitted rapid latitude surveys, and Atmosphere Explorer E made measurements over local time variations without large changes of latitude.

Chapter 3 describes the scientific instruments carried by the spacecraft to meet the objectives of the missions, and Chapter 4 describes the spacecraft.

ORIGINAL PAGE
COLOR PHOTOGRAPH



3

THE SCIENTIFIC PAYLOAD

It was the deep involvement of individuals, both personally and professionally, that brought the Atmosphere Explorer program to full fruition. From the beginning with a small group of scientists who had been studying the upper atmosphere since the early days of the first sounding rockets, the number in the group expanded as the program progressed.

During the exploratory program of space investigation, as mentioned earlier, isolated measurements provided much new information after the experimental techniques had been mastered so that the measurements could be made meaningful for productive analysis.

The small group of upper atmosphere physicists recognized that they had some unusual capabilities that, if brought together, would clearly be more productive than if they continued their experiments individually. In particular, their capabilities would offer a major potential if applied to investigating the region of the atmosphere known as the thermosphere, which some of them had dubbed the ignorosphere because of the lack of attention it had had. They realized that it was to their mutual benefit professionally and, of course, personally–they liked doing work in this challenging field–to get together, define, propose, and sell the next step in exploring the upper atmosphere; namely, the Atmosphere Explorer.

Thus, the overall process might be viewed as one in which a few people appreciated a set of capabilities, defined goals in which these capabilities could be most effectively used, and subsequently brought together a larger group of people who shared a common interest in achieving these goals. The tools were really the scientific instruments and the data system. The spacecraft made it possible for investigators to conduct experiments using those tools. The Atmosphere Explorer satellites thus became laboratories with which scientific investigators could conduct explicit experiments within the thermosphere.

By 1969, the aeronomy study team had identified five topics that would profit from a detailed investigation in the thermosphere. These were the ion and neutral composition and reaction rates, the energetics of the ionized atmosphere, the processes controlling the spectrum of low-energy electrons, the processes responsible for exciting the airglow, and the global structure and dynamics of the neutral atmosphere. Several other study topics emerged as the team grew and time passed.

The scientific objectives of the Atmosphere Explorer mission concentrated on two aspects of the thermosphere: its chemical processes and its energy conversion processes.

The boxes in figure 24 illustrate the chemical processes, and the circles show the parameters to be measured by instruments carried within the Atmosphere Explorer satellites for investigating the chemical processes. The boxes in

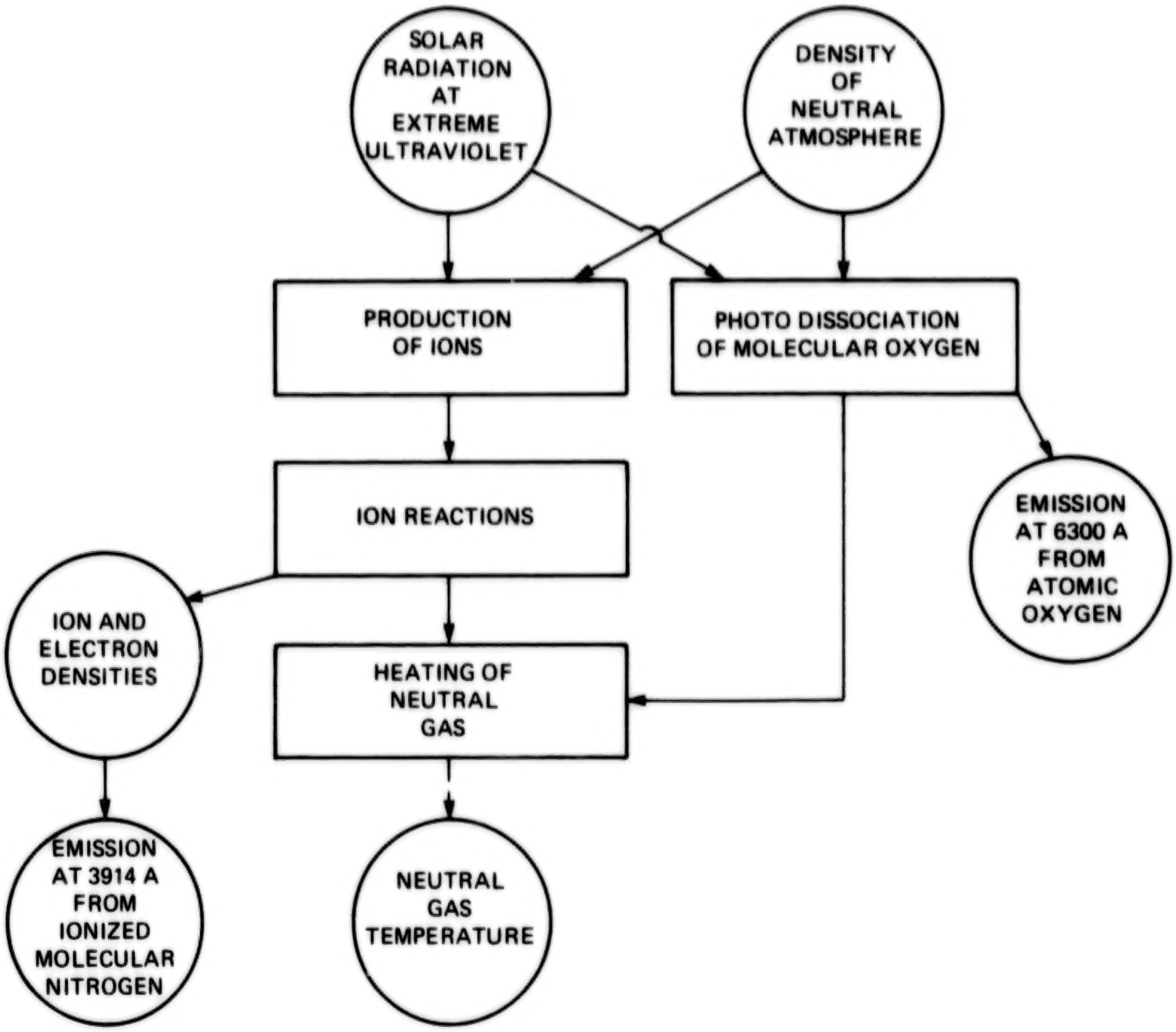


Figure 24. The Atmosphere Explorer program sought information about the chemical processes that occur in the thermosphere. The boxes in this diagram denote these processes, and the circles denote the parameters to be measured by the satellites.

figure 25 show the energy conversion processes, and the circles show the parameters to be measured for studying these processes.

The way in which the various measurements were to be employed to attack specific problems of the thermosphere was first proposed in a feasibility study in 1967 and was more clearly defined by the aeronomy team in a report published in August 1969. Several instruments would be used to investigate ion and neutral composition and reaction rates. The ions produced in the thermosphere by the absorption of solar ultraviolet radiation undergo a variety of reactions with molecules before they finally recombine. The efficiencies with which the ions are converted into other species in the atmosphere depends on the concentrations of neutral particles and on the rates at which the various reactions take place. By measuring the amount of ultraviolet radiation from the Sun and the concentrations of neutral particles, investigators could calculate how many ions would be produced. By measuring the actual

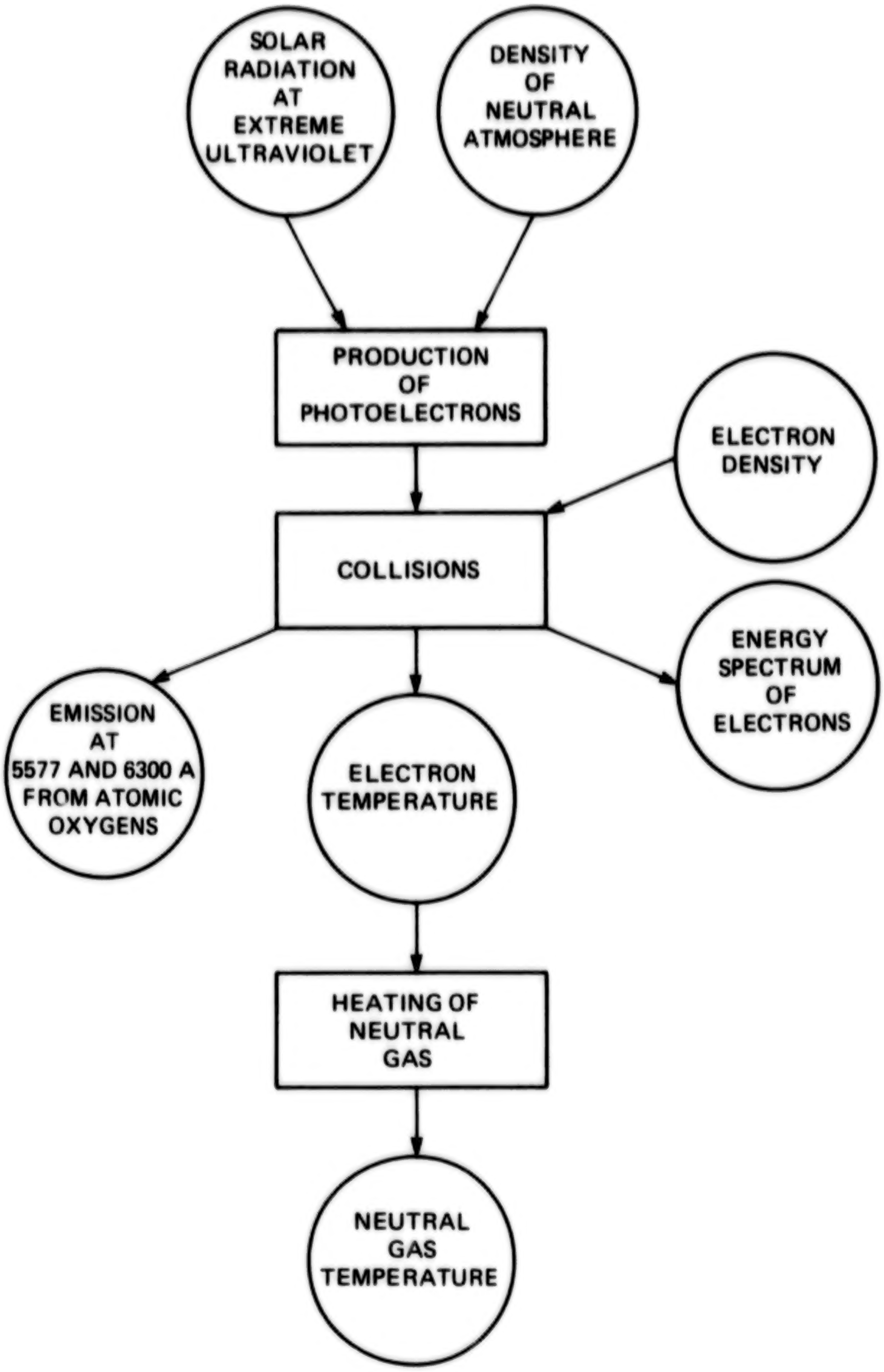


Figure 25. The program also sought information about the energy conversion processes within the thermosphere. The boxes denote these processes, and the circles denote the parameters to be measured.

number of ions present, they would then be able to derive models of the chemistry involved and the true rates at which ions are produced. Such analyses were expected to provide insight into the role played by minor constituents of the atmosphere, by vibrationally excited molecules, and by processes of ion transportation, all of which were expected to be involved in determining the amount of ionization within each of the various regions of the thermosphere.

Photoelectrons produced in the thermosphere are the main source of energy for heating ions and electrons. From the spectrum of photoelectrons measured by instruments carried by Atmosphere Explorer, scientists can calculate the rate of heating of the surrounding electrons. The electron temperature can then be calculated by balancing the electron heating rate with the electron cooling rate. Cooling occurs when the energy of electrons is passed to ions and neutral gas, the concentrations of which can be measured. Comparison of the measured and calculated values of electron temperatures allows improved coefficients to be calculated and used in theoretical models for these important processes that occur in the thermosphere. Because the temperature of the ions and neutral gas particles were also measured, a similar analysis was made of ion heating and cooling. The ions are heated by collisions with electrons and cooled by collisions with neutral gas molecules.

At that time, it was quite clear to the Atmosphere Explorer team that a unique solution could not be derived from measurements made during a single passage through a low-altitude perigee, but that data would be required from many orbits taken at different locations and different times. The Atmosphere Explorer satellites were important here because they could make repeated passages through the lower thermosphere without their orbits being destroyed.

To study the processes that control the numbers of low-energy electrons with different energies, the aeronomy team proposed to interpret in detail a select few of the measured spectra of electron energy. This study was expected to uncover inadequacies in understanding the sources of low-energy electrons, as well as the processes by which their energies are degraded in the thermosphere. The study was to concentrate initially on data from the low-altitude region of the thermosphere in which the low-energy electron spectra are in local equilibrium (i.e., as many electrons are being released as are being absorbed at each energy level).

The Atmosphere Explorers examined the spectra of photoelectrons from low and midlatitudes. The team expected such spectra to vary smoothly with altitude, with how far the Sun was from overhead (zenith angle), and with activity on the Sun. If the initial data from the orbit confirmed these assumptions, the team would then make a detailed study of a number of spectra representative of conditions at about 150 and 250 km at low and high solar zenith angles and at extremes of solar activity.

Simultaneous measurements of density of neutral atmospheric constituents and the local flux of extreme ultraviolet radiation enabled the experimenters to calculate the spectrum of photoelectron production to clarify uncertainties in our knowledge of the states of ions produced by photoionization. They then calculated the expected photoelectron spectrum to compare it with the measured spectrum. This comparison reduced the uncertainties about inelastic collision cross sections by using data on the emission rates of the green and red lines of atomic oxygen in the locality of the thermosphere where the measurements were made.

The study would first be done under quiet geomagnetic conditions and would then be repeated

during a period of geomagnetic disturbance to determine if low-energy electrons are produced by geomagnetic storms as well as by photoionization.

Also proposed was a study of secondary electrons coming from the aurora similar to the study of photoelectrons. The shape of the spectrum might be used for such an analysis, but the study would be enhanced if measurements could be made in orbit of the emission of radiation at 4278 A or of the omnidirectional flux of electrons over a range of energies up to 10 keV.

At the time when the Atmosphere Explorer satellites were being planned, measurements of the distribution of auroral particles with energy and pitch angle had not provided many clues as to the mechanism that precipitates these particles, but at least two mechanisms appeared to be indicated. Observations in the late 1960's of nearly monoenergetic streams of auroral electrons suggested a local accelerating electric field. By comparing selected low-energy spectra measured in nighttime auroras with theoretical spectra calculated from satellite measurements of neutral and electron densities, the scientists expected to resolve uncertainties in how auroral spectra are produced and to uncover evidence for the local acceleration of auroral electrons.

It was also decided that the Atmosphere Explorers should be used to study the airglow both during the daytime and at night. The dayglow studies compared actual emissions at 6300 A with theoretical calculations based on the measured neutral composition to determine the rate at which excited atoms of oxygen lose energy. These comparisons were expected to answer questions about the emission rate in daytime, the direct photodissociation of molecular oxygen, and the rotational and vibrational distributions of ionized nitrogen molecules.

The nightglow studies were visualized as simpler versions of the dayglow studies. One important aspect was to explore the role played by photoelectrons in the predawn enhancement of the airglow. Another was to investigate the processes responsible for enhancing the twilight red line of oxygen at midlatitudes during magnetic storms.

The studies of the aurora that were possible with Atmosphere Explorers fell into two distinct categories. When a single stable auroral form could be identified, the spacecraft could provide altitude profiles for evaluating the role of secondary electrons in producing emission at 5577 A, thereby checking the theory of auroral emissions. Similar studies of the oxygen red line and the nitrogen line at 4278 A could provide experimental checkpoints of the energy sources for the aurora.

The spacecraft also provided gross average measurements through many auroral features for evaluating the influence of auroral heating on atmospheric dynamics during magnetic storms. Direct measurement of temperature on the spacecraft, coupled with the other data, provided a much-needed step toward understanding the behavior of the neutral atmosphere during magnetic storms.

Finally, the Atmosphere Explorers were expected to provide much new information about the global structure and dynamics of the neutral atmosphere because parameters could be measured to much deeper levels within the thermosphere than had been possible with earlier satellites.

The investigators expected to solve the longstanding question of whether the so-called "seasonal anomaly" in the F2-layer was in part caused by differences in composition. In addition, the winter polar bulge in the atmosphere

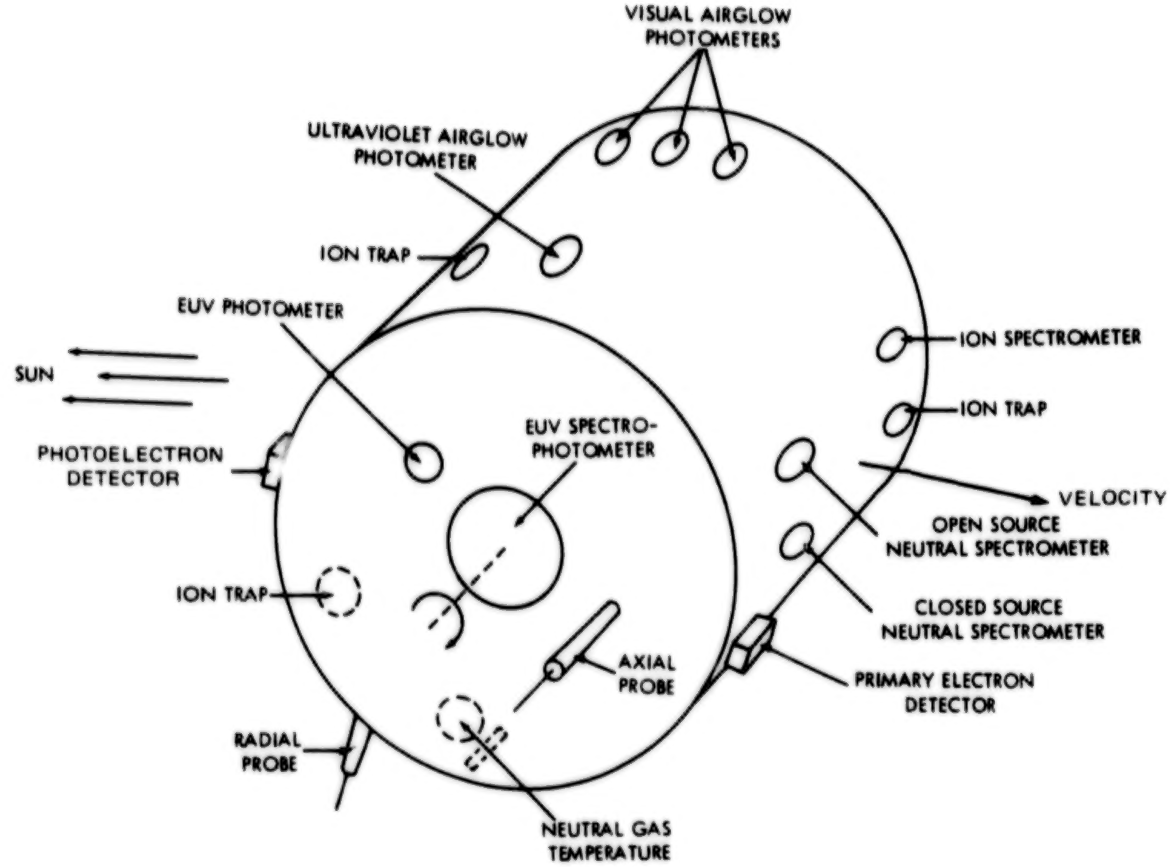


Figure 26. This drawing illustrates how the science payload could be located around the spacecraft to suit the characteristics of the instrument to the capabilities of the spacecraft in its two modes of operation—spun and despun.

caused in part by helium would be investigated in detail so that it might be theoretically understood. Experimenters expected to obtain data for calculating the global high-altitude winds that had been postulated to explain a number of phenomena taking place in the upper atmosphere, including the maintenance of the ionosphere during the night.

The aeronomy team also anticipated a better understanding of the thermal tides at high altitudes and the nature of the heat sources provided by magnetic storms. Atmosphere Explorer could also be used to determine how much gravity waves contribute to the mixing of the high atmosphere.

SCIENTIFIC INSTRUMENTATION

The Atmosphere Explorer program was specifically directed toward the study of the chemical and energetic processes that control the structure of the thermosphere. Prime emphasis for the photochemical study was placed on the lower thermosphere, which had not been explored by earlier satellites.

Seventeen scientists were selected–14 provided instruments and 3 were theorists. These scientists were organized as an aeronomy team to provide a comprehensive concerted attack on the many problems associated with understanding the themosphere. The various instrument sensors were located on the spacecraft as

shown in figure 26. Five of the instruments (ion spectrometers, neutral gas spectrometers, and an ion trap) looked forward while operating in the despun mode in the direction the spacecraft was traveling. The extreme ultraviolet (EUV) instruments were located on an end surface of the satellite; the spectrophotometer was mounted on a platform that could point it toward the Sun. The photoelectron and primary electron sensors were located around the periphery of the spacecraft.

The instruments for Atmosphere Explorer were selected on the basis of laboratory equipment and equipment flown on sounding rockets and other satellites. The apparatus changed slightly between the three Atmosphere Explorers. Table 2 shows these differences and lists the investigators, their affiliations, their instruments, and some details of the instruments.

SOLAR ULTRAVIOLET MEASUREMENTS

An important measurement made by the Atmosphere Explorer satellites was the amount of ultraviolet radiation flowing from the Sun into the Earth's atmosphere and its absorption at various levels. These measurements would allow the team to determine how the radiation at various frequencies is dissipated in the thermosphere. Two instruments were flown for this purpose: a multichannel spectrophotometer and a filter photometer.

Spectrophotometer

The spectrophotometer measured the solar extreme ultraviolet flux in the wavelength range from 140 to 1850 A at all altitudes of spacecraft operation. Measurements of the attenuation by the atmosphere of solar emissions at selected wavelengths contain information on the composition and temperature of the neutral atmosphere to complement the measurements of these parameters by other instruments.

Spectrophotometers for analyzing solar radiation at extreme ultraviolet wavelengths had previously been flown on rockets and satellites. Aerobee-150 rockets had been equipped with grating focusing monochromators designed to point at the Sun and scan substantial parts of the spectral region from 30 to 1300 A. A focusing monochromator, covering the range from 250 to 1300 A, was also used on Orbiting Solar Observatory III. On the Orbiting Geophysical Observatory, an instrument consisting of a compact assembly of six grating monochromators of a new nonfocusing type covered a range from 170 to 1700 A. This instrument was modified considerably to make it suitable for use in the Atmosphere Explorer mission.

The Atmosphere Explorer instrument (figure 27) consisted of 24 grating monochromators, 12 of which could be telecommanded either to execute 128-step scans (each covering a relatively small section of the total spectrophotometer's range of wavelengths) or to maintain one of several sets of fixed wavelength positions selected by command. The remaining 12 nonscan monochromators operated at permanently fixed wavelengths and viewed only a small fraction of the Sun's disk, except for one of them, which viewed the entire Sun at the wavelength of hydrogen Lyman alpha. Ten of the 12 scan-capable monochromators viewed the entire solar disk. Their primary function was to measure the total average flux from the Sun, independent of the variable distribution of ultraviolet-emitting sources across the disk. The narrow angular fields of view of the fixed-wavelength monochromators were chosen to allow a good height resolution of atmospheric absorption to altitudes as low as 90 to 100 km.

Each of the monochromators used grazing incidence for a planar grating of suitable ruling. The diffracted radiation was analyzed by a special collimator about 3 cm long. The degree of collimation was sufficiently modest to

Table 2
Experiments and Engineering Measurements

Investigator	Organization	Manufacturer	Instrument	Instrument Characteristics				
				Flights	Weight (kg)	Power (watts)	Detector	Parameters
H. Hinteregger	AFGL	BBRC	Solar EUV Spectrometer (EUVS)	C, D, & E	11.9	8.5	Channel electron multipliers (CEM's)	140 to 1850 A
D. Health	GSFC	BBRC	Solar EUV Filter Photometer (ESUM)	C, D, & E	6.8	2.25	Spiraltron electron multiplier (SEM) and EUV diodes	40 to 1300 A
C. Barth & I. Stewart	U. of Col.	U. of Col.	UV Nitric Oxide (UVNO)	C & D	6.8	8.0	Photomultiplier tubes (PMT's)	2150 to 2190 A
P. Hays	U. of Mich.	U. of Mich.	Airglow Photometer (VAE)	C, D, & E	8.6	4.5	PMT's	6300, 5577, 4278, 3371, 5200, 7319 to 7330 A
A. Nier	U. of Minn.	U. of Minn.	Open-Source Neutral Mass Spectrometer (OSS)	C, D, & E	7.3	9.0	Electron multiplier	1 to 46 amu
A. Hedin (D. Pelz)	GSFC	GSFC/U. of Mich.	Closed-Source Neutral Mass Spectrometer (NACE)	C, D, & E	8.3	18.0	Electron multiplier	1 to 46 amu
N. Spencer	GSFC	GSFC/U. of Mich.	Neutral Atm. Temp. Exp. (NATE)	C, D, & E	9.2	17.5	Electron multiplier	T_g, N_2, V_w
K. Champion	AFCRL	Ball Aerospace	Atm. Density Accel. (MESA)	C, D, & E	9.5	19.5	Accelerometer	Neutral density
W. Hanson	U. of Tex. Dallas	U. of Tex. Dallas	Planar Ion Trap (RPA)	C, D, & E	5.1	6.0	Electrometer	T_i, N_i, M_i, drift velocity
L. Brace	GSFC	Universal Monitor	Cylindrical Electrostatic Probe	C, D, & E	1.9	2.5	Electrometer	T_e, N_e, N_i, M_i
J. Hoffman	U. of Tex. Dallas	U. of Tex. Dallas	Magnetic Ion Mass Spectrometer (MIMS)	C & D	7.3	7.0	Electron multiplier	1 to 64 amu
H. Brinton	GSFC	Aero Geo Astro	Positive Ion Mass Spectrometer (BIMS)	C & E	4.1	1.5	Electrometer	0.5 to 72 amu
R. Hoffman	GSFC	GSFC	Low-Energy Electron Exp. (LEE)	C & D	4.2	2.2-C 2.5-D	SEM's	0.2 to 25 keV
J. Doering	J. H. Univ.	APL	Photoelectron Spectrometer (PES)	C, D, & E	4.1	2.5	Johnson electron multiplier	Photoelectron spectra
C. Rice & S. LaValle	Aerospace Corp.	Aerospace Corp.	Capacitance Manometer	C, D, & E	2.7	1.5	Electrometer	Pressure
C. Rice (V. Carter)	Aerospace Corp.	Aerospace Corp.	Cold Cathode Ion Gage Range	C, D, & E	2.5	1.5	Diaphragm	Pressure
E. Young	GSFC	GSFC	Temperature Alarm	C, D, & E	0.9	1.3	Grid wire	Aerodynamic heating

T_e - electron temperature
T_i - ion temperature
T_g - gas temperature
N_e - electron density
N_i - ion density
M_i - ion mass
V_w - neutral wind
BBRC = Ball Brothers Research Corp.
AFGL = Air Force Geophysics Laboratory
AFRCL = Air Force Cambridge Research Laboratory
amu = atomic mass unit
APL = Applied Physics Laboratory

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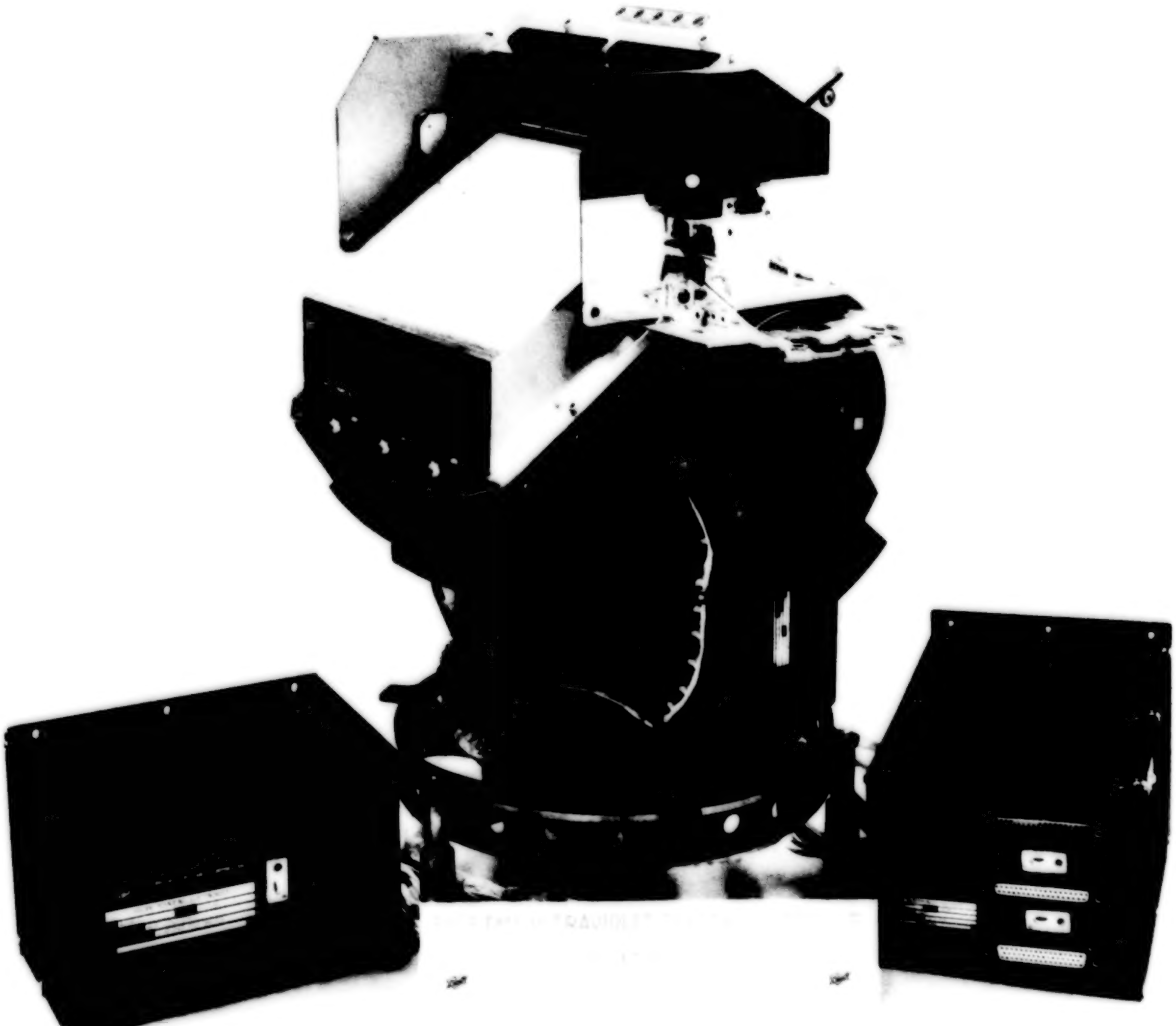


Figure 27. The solar extreme ultraviolet spectrometer was designed to measure solar radiation and to determine how the radiation is being absorbed by the thermosphere.

accomplish adequate transmission. Wavelengths were scanned by rotation of the collimator about an axis perpendicular to the plane of dispersion. The diffracted radiation emerging from the exit collimator was counted by a photoelectric detector.

Filter Photometer

The filter photometer (figure 28) used detectors, filters, and electronic signal processing equipment that were readily available from commercial sources or that had been tested earlier by the experimenters. The instrument consisted of four electron multipliers behind a moving eight-position filter wheel. Six of the eight sections of the wheel carried filters of thin metal films that were transparent to solar ultraviolet radiation over certain wavebands. Table 3 lists filter materials and filter transmission ranges, together with the principal ions that would be produced by solar radiation in each range.

Table 3
Extreme UV Radiation
Filter Characteristics

Material	Transmission Range (A)	Positive Ions
Indium	750 to 1100	O_2
Titanium	350 to 550	O
Bismuth	350 to 700	N_2
Aluminum/ carbon	200 to 500	N_2 O
Aluminum	200 to 800	N_2 O
Tin	500 to 800	N_2

In addition, the instrument had three aluminum oxide diodes, two of them with filters, for recording the solar irradiance over the full range of orbital altitudes. This permitted monitoring of the solar radiation at altitudes where the use of multipliers with high voltage in open structures was unsafe.

Two types of windowless photoelectric detectors were used: Spiralton electron multipliers and photodiodes. Both detectors used opaque photocathodes. The former possessed high sensitivity to low-light levels, whereas the latter could operate safely at high intensity when the multipliers had to be turned off.

Two modes of operation were possible. In the spin mode, the filter wheel was stepped at a time determined by a Sun sensor or a spacecraft nadir pulse, which provided a trigger on each revolution of the spacecraft. In the free-running mode, the filter wheel was stepped automatically every 16 seconds.

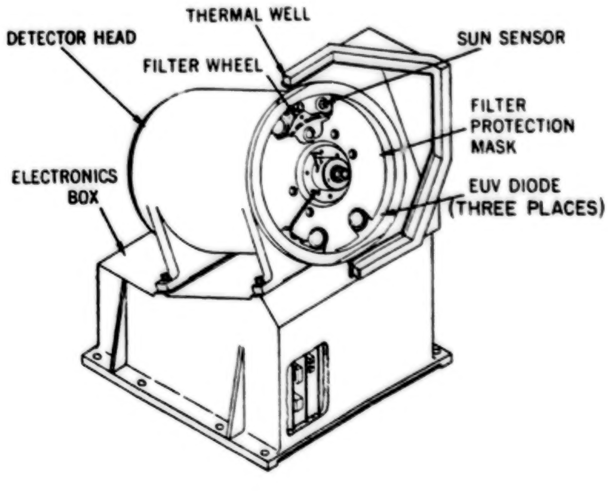


Figure 28. A filter photometer was used to monitor solar ultraviolet radiation over different wavebands.

Neutral Particles, Number Densities, and Temperature

The composition and state of the neutral atmosphere within the thermosphere were of prime importance to the team members. Because the

measurements needed were complex and difficult, two instruments were recommended for measuring the composition, and a third instrument was recommended for measuring the temperature.

The aeronomy team wanted to determine specific facts about the thermosphere, such as the instantaneous and global distribution of neutral hydrogen, helium, atomic and molecular oxygen, nitrogen, and argon, and the total mass density above 120 km. In addition, they needed measurements of trace constituents within the mass range of 1 to 46 amu. Such information would be invaluable to the aeronomy team for their comprehensive study of the chemical, energetic, and dynamic processes that control the structure of the thermosphere.

Although neutral mass spectrometers were proven instruments, two kinds had special features that had to be considered for the Atmosphere Explorer mission: open-source spectrometers and closed-source spectrometers. An open-source mass spectrometer can best detect reactive gas species such as atomic oxygen and hydrogen. However, the instrument has an inherent difficulty in focusing on particles that approach it from the side rather than head on, so that the measurements are most accurate if obtained when the axis of the spectrometer coincides with the velocity vector of the spacecraft. In contrast, a closed-source spectrometer produces the most precise measurements of nonreactive gases and provides a measure of the sum of atomic and molecular oxygen because the atomic oxygen recombines on the surfaces before ionization. This measurement is obtained over the entire forward-looking hemisphere, largely independent of side energies.

Because using two instruments together appeared to give the greatest promise of obtaining good measurements of the composition of the lower thermsophere, NASA Headquarters selected this combination for the Atmosphere Explorers.

Open-Source Neutral Mass Spectrometer

The open-source instrument (figure 29) employed a mass spectrometer with an electron bombardment ion source, together with a double-focusing, magnetic deflection, Mattauch-Herzog type of mass analysis system. The ion source was designed to minimize collisions and was similar to those flown earlier in sounding rockets.

Because the instruments would cover the mass range from 1 to 56 amu, using a common trajectory for all the ions in this magnetic deflection instrument would have led to undesirably high or low ion-accelerating voltages. To overcome such a problem, two ion collectors were used: one to collect high masses between 7 and 56 amu, and one to collect the low masses between 1 and 8 amu. This arrangement, already flown successfully in sounding rockets, also had the advantage that two different constituents of the atmosphere could be examined at the same time (e.g., helium and molecular nitrogen).

The analyzed ion currents were measured with electron multipliers and electrometer amplifiers. The electrons used to ionize the neutral particles were emitted from a heated tungsten filament.

Three modes of spectral scanning were employed. In the mode used most of the time, the instrument was switched from one mass position to the other, counting ions for a fixed time, to give meaningful statistics for all but the rarest constituents. A second mode of

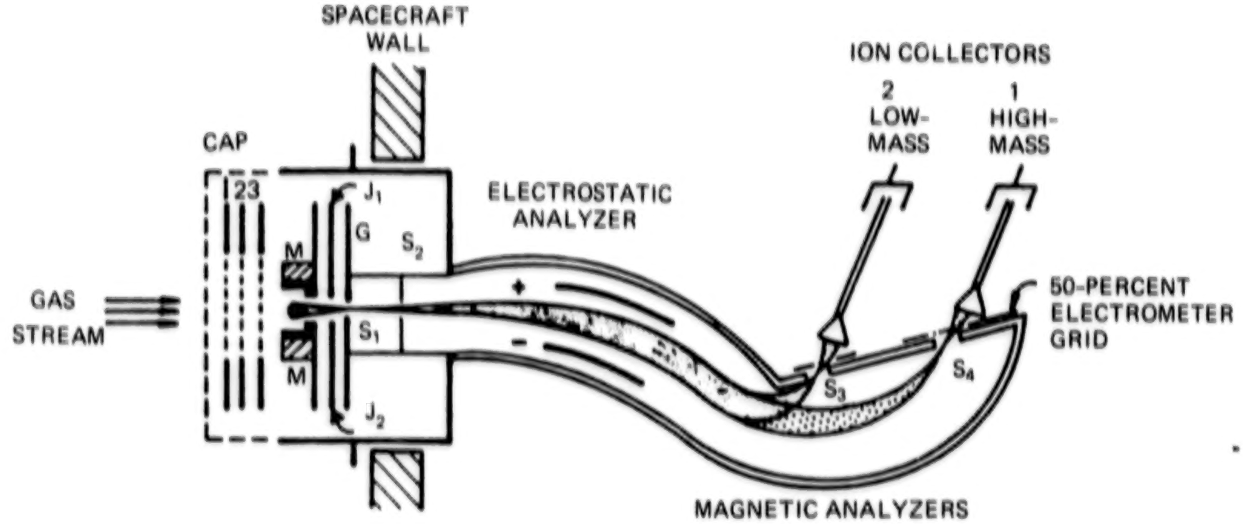


Figure 29. One of the neutral mass spectrometers used an open source to detect reactive gases. This double-focusing configuration allowed two constituents of the atmosphere to be examined simultaneously.

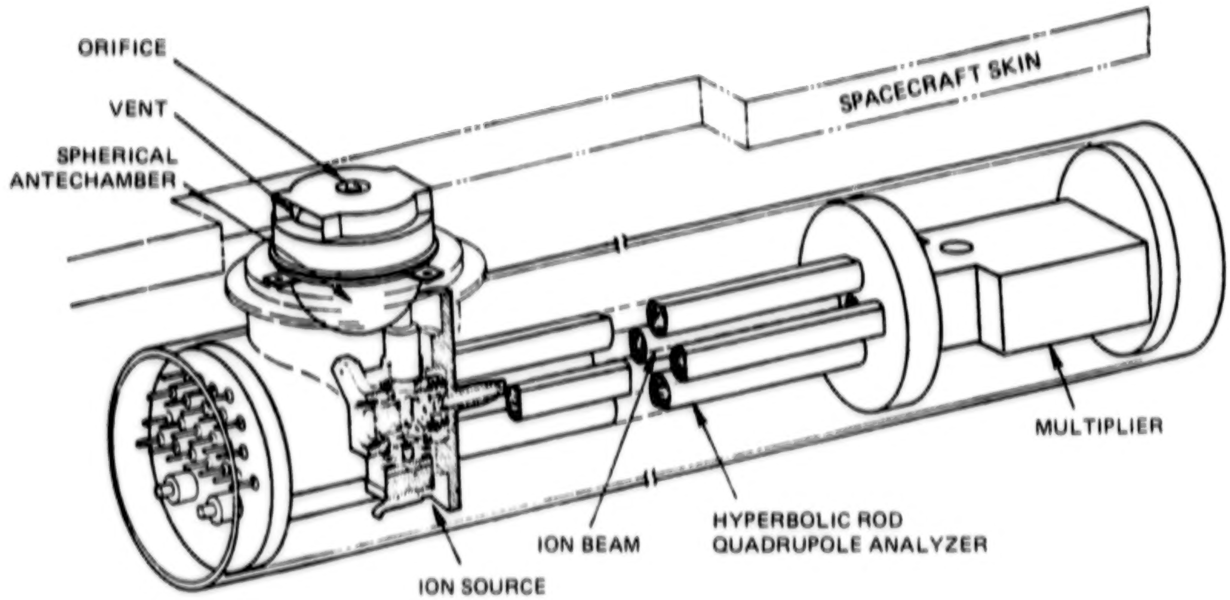
operation scanned an entire spectrum, as was done during rocket flights. This mode permitted an occasional view of other mass positions to see how impurities were behaving, to look for possible rare constituents, and to ensure that, when the instrument was used in the first mode, it was accurately aligned to detect the peak of the required mass number distribution.

A third mode permitted two masses that were being collected simultaneously to be collected continuously so that modulation caused by spinning of the satellite could be observed. This modulation enabled scientists to calculate the temperature of the thermosphere for comparison with the temperature determined from other measurements.

Closed-Source Neutral Mass Spectrometer

The closed-source instrument was developed as a direct extension of a similar instrument flown on an Orbiting Geophysical Observatory. The sensor was a quadrupole mass spectrometer employing a spherical antechamber (figure 30). The atmosphere entered the chamber through a knife-edge orifice. This gold-plated antechamber was similar to one developed for a San Marco-C neutral composition experiment. It provided a thermal accommodation of the particles entering the instrument, before their masses were measured, as well as a known relationship between the density within the chamber and that outside.

The sensor consisted of a dual ion source, a quadrupole analyzer with hyperbolic rods, and an off-axis electron multiplier. The spectrometer had a mass range of 1 to 46 amu with a resolution better than one mass unit at all masses over the range. The electronic system consisted of an electrode power supply and emission regulator, an RF oscillator, a detector, and a logic subsystem.



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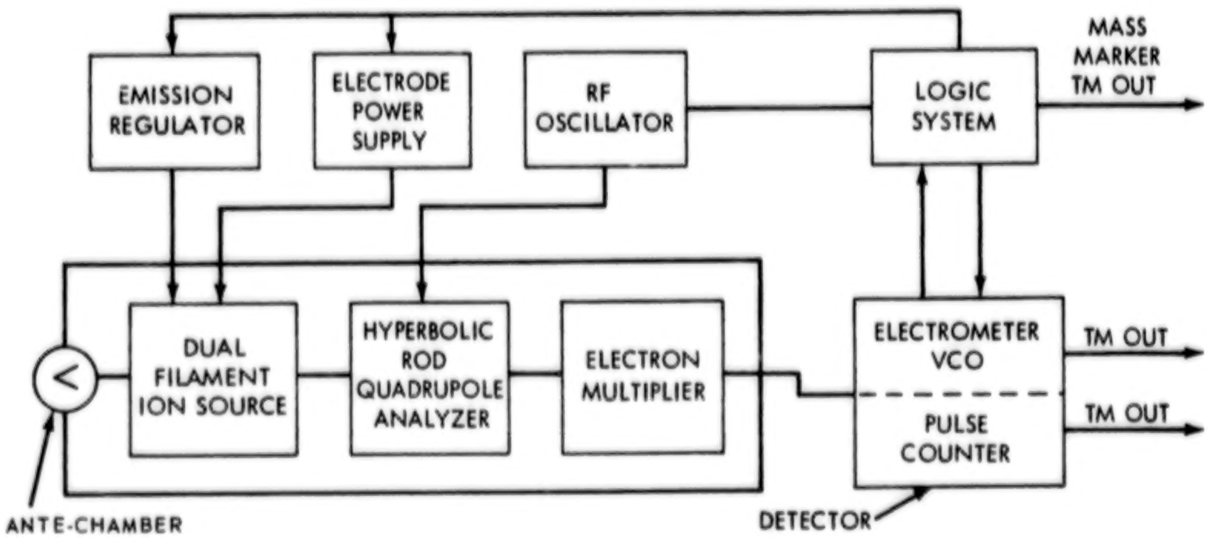

B

Figure 30. The closed-source neutral mass spectrometer measured nonreactive gases: A shows how the sensor was mounted to gain access to the thermosphere, and B illustrates the technique used.

Automatically controlling the sensitivity and pulse-counting of the ion source allowed the instrument to measure density from an altitude of about 125 to 1000 km.

In its normal operating mode, the instrument measured all masses in its operational range, with emphasis on those for hydrogen, helium, oxygen, nitrogen, and argon. Additional operational modes were designed to seek minor atmospheric constituents within this mass range.

Correlation of the neutral measurements with simultaneous measurements by the open-source mass spectrometer, the solar extreme ultraviolet spectrophotometer, and density accelerometer experiments was expected to provide new insight into *in-situ* measurement techniques–a comparison that had not previously been possible using instrumentation on board a satellite.

Early experience with the Orbiting Geophysical Observatory had indicated that background gas limits the upper altitude measurements of molecular nitrogen and atomic oxygen to about 550 and 700 km, respectively. Because the closed-source spectrometer measured most of the atomic oxygen in molecular form after surface recombination, the measurements of ambient molecular oxygen were expected to be limited to altitude ranges in which the ratio of molecular to atomic oxygen was not less than 0.1 (i.e., below about 210 km). However, if atomic oxygen densities proved higher than expected, the altitude limit would be lower. The lower altitude limit of operation was set by the maximum density to which the ion source could respond linearly or by gas dynamic flow effects. The ion source was tested to densities of 3×10^{12} parts per cm^3, which, with consideration of the ram enhancement in the closed source, would limit the low altitude measurement for all gases to about 139 km at zero angle of attack. However, it was expected that this could be extended to a slightly lower altitude by using data from angles of attack near 90 degrees.

One of the important problems faced by the Atmosphere Explorer team was the uncertainty of the measurement of atomic oxygen, which was the major atmospheric constituent over much of the orbit. Difficulties had been encountered in calibrating spectrometers to atomic oxygen and in studying the surface effects of that gas. Surface effects for nonreactive gases were sufficiently understood to expect an uncertainty of less than 15 percent in the measurement.

Another important measurement of the neutral atmosphere was that of its temperature, which required the use of another instrument that also relied on a mass spectrometer.

Neutral Atmosphere Temperature Experiment

The temperature of the neutral gas at the location of the satellite can be determined by measuring the velocity distribution of molecular nitrogen or atomic oxygen. To make this measurement, the instrument, in the spinning mode, rotates a chamber with an orifice in the orbit plane through all angles relative to the velocity vector of the spacecraft. The atmospheric gas density inside the chamber varies according to a simple relationship in which one of the terms is governed by the velocity distribution of the particles of gas (namely, their temperature) and the velocity of the spacecraft.

The gas density is measured within the chamber by tuning a quadrupole mass spectrometer to a fixed mass (e.g., molecular nitrogen (28 amu)). The density of the nitrogen is determined by ionizing a percentage of the gas particles and

counting the ions produced with a multiplier. The first satellite version, which used an omegatron, was built and tested on San Marco-C. For the Atmosphere Explorer, the omegatron was replaced by a small quadrupole. The result was better signal-to-noise ratio so that a greater altitude range of operations was possible and data transmission was much improved.

Thus, to determine the density and temperature of the atmosphere through which the satellite passed, the instrument measured, as a function of time, the variation of the density within the chamber of the relatively plentiful and nonreactive molecular nitrogen. This measurement, together with the velocity of the satellite, the orientation of the orifice of the gage to the path of the spacecraft through the air, and the temperature of the gage, provided inputs for calculating the density and temperature of the molecular nitrogen outside the spacecraft.

An alternative mode for measuring kinetic temperature made use of a baffle consisting of a small rectangular plate mounted in front of the entrance orifice of the mass spectrometer. As the satellite spun, a wake of neutral particles formed by the baffle in front of the orifice caused a "bite-out" of the density maximum. Some atmospheric gas that would have entered the chamber was prevented from doing so. The depth and shape of this bite-out for a particular gas was dependent on the gas temperature. Although it had not been tried beforehand, this measurement of temperature was incorporated in the Atmosphere Explorer experiment as the primary means of determining the temperature of the thermosphere's neutral gases. It required merely the simple addition of a baffle to the existing instrument. This baffle was designed so that it could be moved in or out of position by ground command. In addition, the baffle system was the only available means for measuring temperature when the satellite was operating in its despun mode. For another purpose, as the baffle was moved uniformly in front of the orifice, it provided a signal for determining wind direction.

The instrument (figures 31 and 32) was capable of measuring the density of nitrogen molecules to altitudes of 370 to 540 km for exospheric temperatures of 800 and 1500 K, respectively, and winds to 600 km.

To supplement measurements made by this instrument, the density of the thermosphere was also determined from the motion of the spacecraft as it passed through perigee and was retarded by atmospheric drag.

Atmospheric Density Accelerometer

Three single-axis miniature electrostatic accelerometer (MESA) systems mounted orthogonally measured the effects of drag. These instruments also formed part of the engineering payload of the spacecraft. Two of the accelerometers were positioned with their sensitive axes in the X-Y plane of the spacecraft. The third sensor was aligned with the spacecraft's Z-axis. All three units were located near the vehicle's center of mass to minimize accelerations due to the dynamics of the vehicle. The sensor portion of each instrument utilized a proof mass consisting of a hollow cylinder with a centrally located flange. The proof mass was suspended in its radial axes by electric fields generated by the eight support electrodes. This permitted free movement of the proof mass along its longitudinal, or sensitive, axis. The proof mass flange formed the moving plate of an extremely sensitive capacitance bridge with the forcer electrodes on either side. Acceleration of the satellite along the sensor sensitive axis caused motion of the proof mass from its

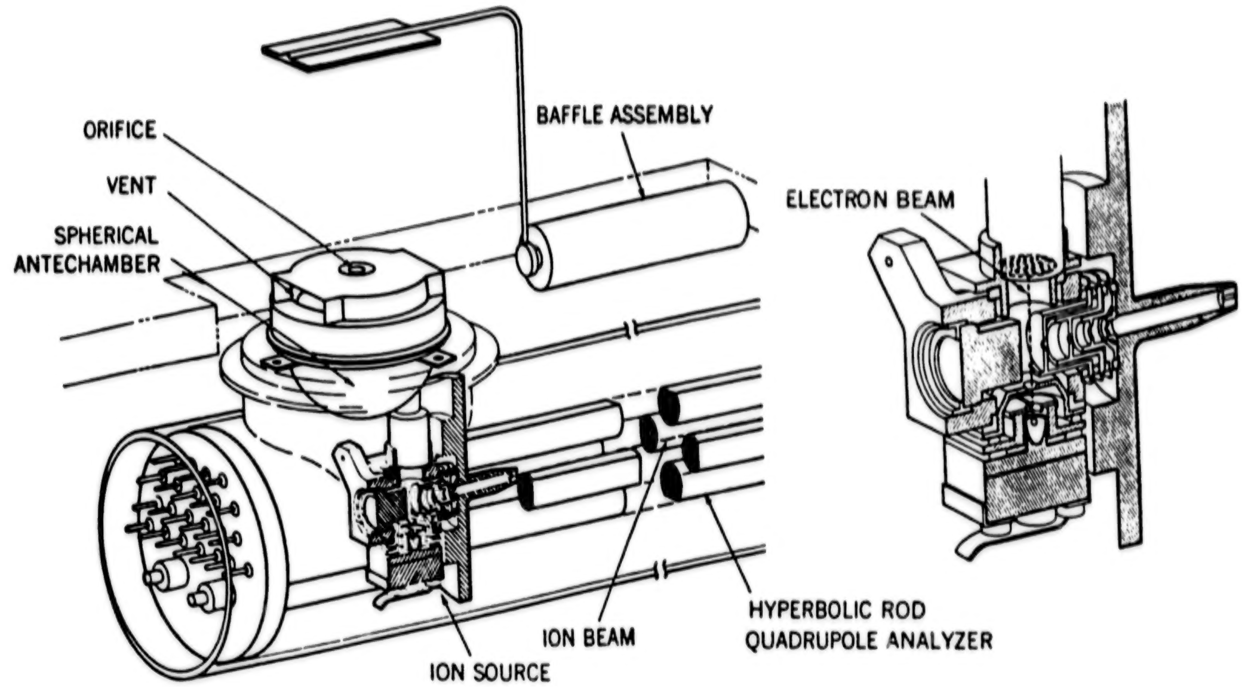

Figure 31. A mass spectrometer was also used to determine the temperature of the neutral gases using a spherical antechamber to first measure the atmospheric density of molecular nitrogen. This drawing shows the quadrupole analyzer and the location of the sampling chamber and a baffle assembly.

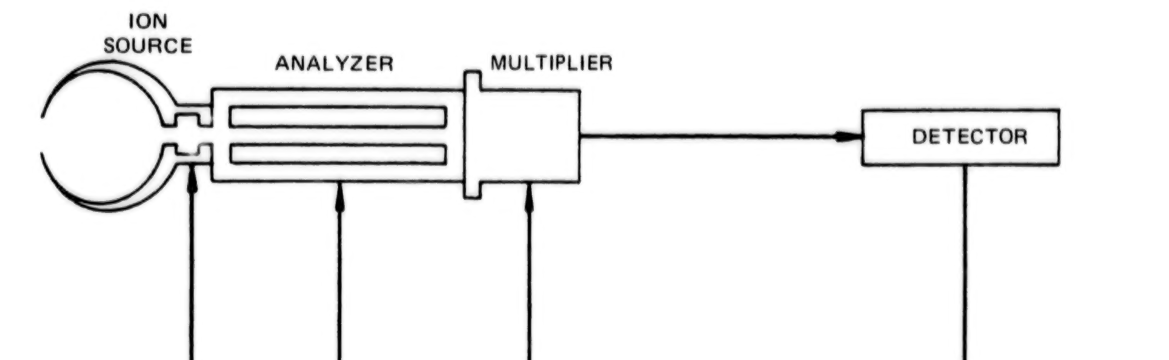

Figure 32. Simplified schematic of the neutral atmosphere temperature experiment.

null or zero acceleration position. This motion caused an unbalance in the bridge. Electrostatic potentials were applied to the forcer electrodes to restore the proof mass to its null position. The direct current output signal of the instrument was fed to a precision analog-to-digital converter to provide a digital pulse rate directly proportional to the applied acceleration.

The neutral density of the atmosphere in the altitude range from 120 to 400 km was measured by the deceleration of the satellite due to atmospheric drag. This measurement added to earlier work performed with falling spheres and observations of the decay of satellite orbits.

Plasma Measurements

Another important group of instruments was concerned with the characteristics of the charged particles that make up the cool plasmas of the thermosphere. Studies of the chemistry of the lower thermosphere require simultaneous measurement of the incoming solar ultraviolet radiation, the neutral particles, and the resultant concentrations of charged particles. At higher altitudes, both ion and neutral composition data are needed to determine the rate coefficients for the reactions that govern the production and the subsequent loss of light ions. In addition, measurements of charged particles are needed for correlation with observations of the airglow and with latitudinal variation of electron temperatures in the thermosphere.

Positive Ion Mass Spectrometer

The Bennett ion mass spectrometer had been proven during flights of other vehicles. The instrument originally proposed for Atmosphere Explorer in 1969 was a direct descendant of similar instruments flown on Orbiting Geophysical Observatories and Atmosphere Explorer B. This instrument made continuous high-resolution measurements of thermal positive ions between 1 and 36 amu, sweeping the mass range in 5 seconds, and could detect ion concentrations ranging from 10 to 2 million ions per cubic centimeter.

The instrument could also be commanded to switch to a mode of operation that doubled the spatial resolution of the data. This mode was important at perigee, where conditions in the atmosphere were expected to be changing rapidly with altitude. This "high mass only" mode continuously swept the mass range from 4 to 36 amu in a period of 2.5 seconds.

The mass spectrometer was mounted in the forward-looking part of the spacecraft and could operate in both the spinning and the despun modes.

The instrument operated by drawing ions from the surrounding atmosphere by a negative electric field at the orifice. These ions were then accelerated down the axis of the spectrometer by a slowly varying sweep voltage. For each ion mass, a value of the sweep accelerated the ions to the instrument's resonant velocity. The ions that traversed the tube at the resonant velocity gained energy from a radio frequency field in the three analyzer sections of the instrument. The ions could then pass through a retarding potential and reach a collector where they were counted.

The actual spectrometer (figures 33 and 34) flown on Atmosphere Explorer C was an improved version of this earlier 1969 design. It measured ions in the mass range from 1 to 72 amu and a number density range from 5 to 5 million ions per cubic centimeter. Any combination of three mass ranges (1 to 4, 2 to 18, and 8 to 72 amu) could be selected, with each range normally scanned at a rate of once each 1.6 seconds, corresponding to a distance of 12 km along the orbit. The three overlapping

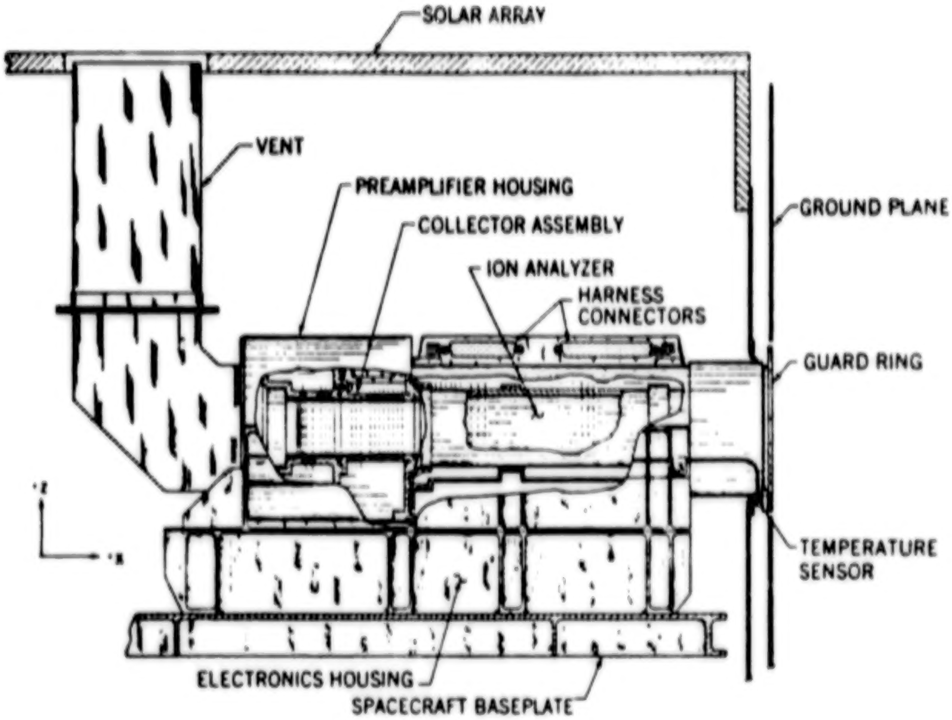

Figure 33. The positive ion mass spectrometer, as installed in an Atmosphere Explorer.

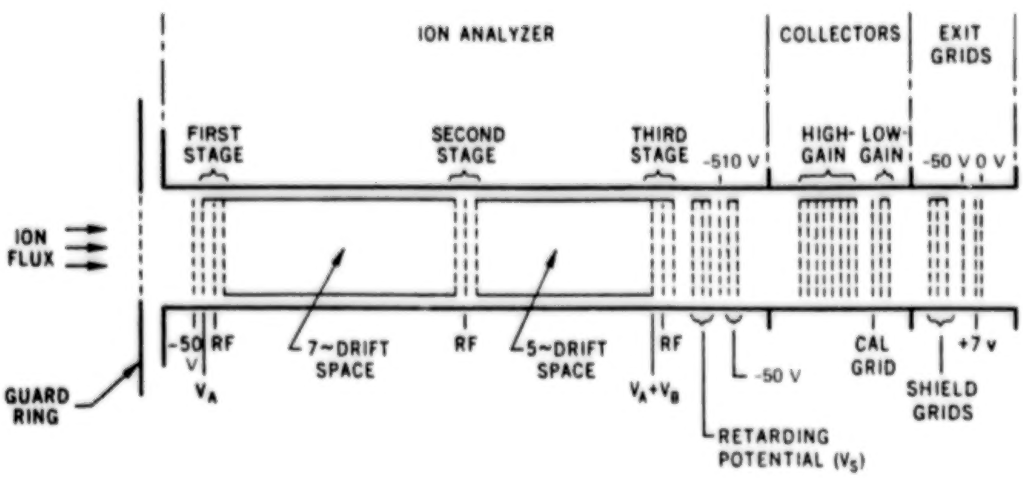

Figure 34. A cross-sectional view of the ion analyzer, the collector, and the assemblies of exit grids.

ranges enabled the mass discrimination within the ion analyzer to be evaluated during flight.

To facilitate measurement at low altitude by reducing the buildup of ram pressure, the analyzer was vented. A multigrid ion current detector was also used. Many characteristics of the instrument could be commanded from the ground to provide great versatility in measurement. These characteristics included mass-scan range and period, sensitivity and resolution, orifice potential, and in-flight calibration. Measurements of individual ion concentrations were expected to be accurate to within 10 percent.

Magnetic Ion Mass Spectrometer

This instrument was designed to measure absolute concentrations of ions in the range 1 to 64 amu. The investigators calibrated it in flight against the retarding potential analyzer and the cylindrical electrostatic probes to give absolute concentration for the species of ions that were detected by this instrument.

The instrument (figures 35 and 36) was a small-aberration magnetic-deflector mass spectrometer consisting of an entrance aperture oriented to look radially from the satellite's equator and a magnetic momentum analyzer. The lens system had zero first-order focusing aberrations along the entire focal plane, where three slits were placed for collecting ions simultaneously in the mass ratios 1:4:16. Following each slit was an electron multiplier-log electrometer amplifier detector.

The three mass ranges covered simultaneously by the scan of the instrument (1 to 4, 4 to 16, and 16 to 64 amu) permitted the measurement of the entire mass range (1 to 64 amu) in 1

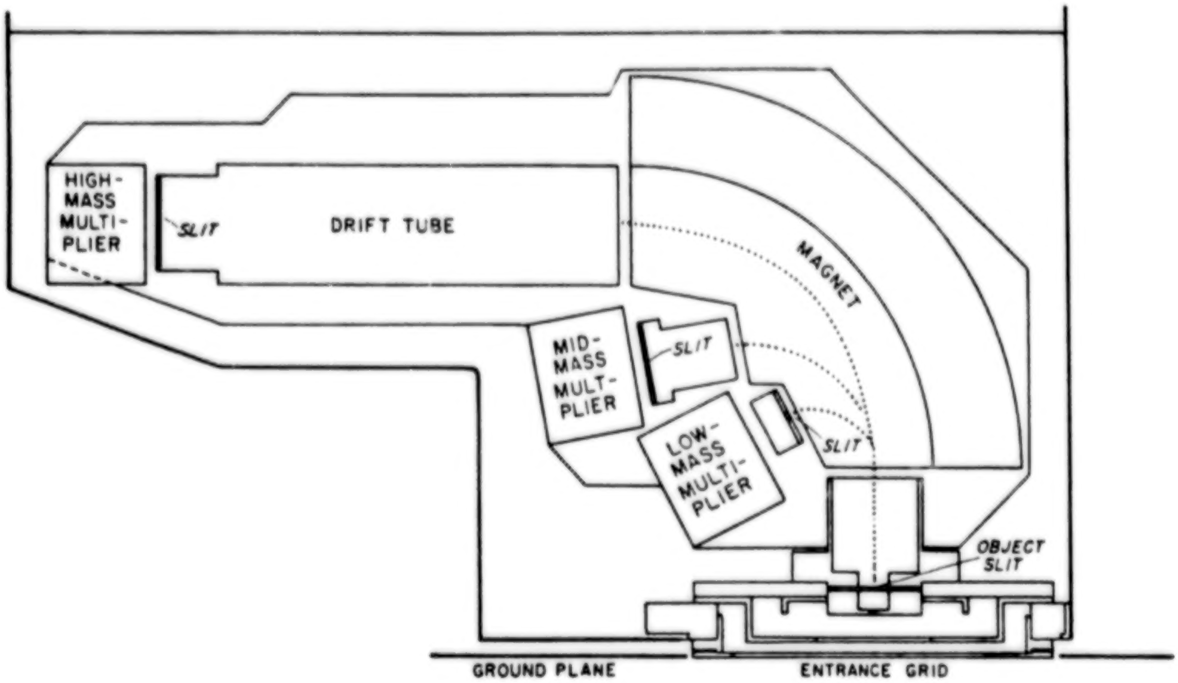

Figure 35. This outline drawing of the magnetic ion mass spectrometer shows the entrance grids and slits, the magnet, the collector slits, and the electron multipliers. The ion trajectories are shown as dotted lines. The collector slits were placed so that ions of mass ratio 1:4:16 could be collected simultaneously.

Figure 36. Magnetic ion mass spectrometer.

second in the main mode of operation. In this mode, a mass peak amplitude detector was used to provide peak amplitude data without transmitting the entire mass spectral scan. An alternate operating mode with a 9-second period of scan extended the mass range to 90 amu. Capability was provided to lock on to any set of mass numbers in the ratio 1:4:16 to give very high spatial resolution (e.g., 500, 250, and 125 m in the low-, mid-, and high-mass ranges, respectively). This alternate mode was most useful during the despun satellite operations because it provided data about the fine structure of ion concentrations within the thermosphere. In the spinning mode, the phase shifts between roll modulation maxima of heavy and light ions determined the vertical component of the individual ion-drift velocities. Values

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from 1 to >250 km/s could be determined. These measurements were important to the study of polar winds in the thermosphere.

Retarding Potential Analyzer

The retarding potential analyzer (figures 37 through 39) was also known as the planar ion trap. It was an improved version of an instrument used in the Orbiting Geophysical Observatory and of similar instruments used on high-altitude sounding rockets. The primary purpose of this instrument was to measure ion temperatures and ion concentrations. These measurements were made with an accuracy of ±3 percent at least once every 40 km of the flight path. The instrument could also determine the drift velocities of ions and the spectrum of energy of both thermal and suprathermal electrons. It was designed to detect negative ion concentrations >0.3 per cm^3 when the spacecraft was in the shadow of the Earth, although the normal positive ion sensitivity was about 1.5 ions per cm^3. Changes in ion concentration along the flight path >0.03 percent could be monitored with a spatial resolution of less than 40 m.

The instrument consisted of four sensor heads, their ground planes, and a main electronics box. Each of the sensor heads contained its own amplifiers. Sensor heads 1 and 4 were located on the forward-facing surface of the spacecraft when it was in the despin mode. Heads 2 and 3 were located 110 and 130 degrees from heads 1 and 4, respectively, as shown in figure 39. Each sensor head consisted of a small cylinder with an aperture at one end through which charged particles passed before striking a solid collector. The path between the aperture and the collector was electrically segmented by a series of grids. By controlling the potentials on the grids, the investigators could screen particles of different energies (e.g., low-energy electrons could be screened out when ions were to be measured).

All the grids through which the ions and electrons entered the chamber of the instrument were square meshes of 25-micrometer wires having either 40 or 20 wires per cm. Heads 2 and 3 were like head 1, except that they had an extra grid separating the entrance grids from the retarding grids. The extra grid could be biased positively to protect the inner grids from ion bombardment when measuring electrons. The other significant difference was that heads 2 and 3 could be biased slightly positive (less than 1.5 volts) on command so that thermal electrons could be encouraged to enter the collector. The collector of head 4, which was called the ion drift meter (IDM), was divided symmetrically into four equal pie-shaped segments, and it had a square aperture with sides parallel to the pie cuts. Therefore, any off-axis flow of ions would result in different currents in the four segments. This permitted the transverse components of ion drift velocity to be measured. When the other sensors faced along the spacecraft's velocity vector, the measured ion energy spectra could be used to deduce the component of ion drift in that direction. Together with the IDM data, therefore, the complete ion drift vector was measured.

Another group of instruments investigated the electrons of the thermosphere, their numbers, and their energies.

Cylindrical Electrostatic Probe

The cylindrical electrostatic probe (figure 40) continued a long line of Langmuir probes used in laboratories and the early high-altitude sounding rockets beginning in 1947. These instruments were used in many Earth satellites, including a group of Explorers and ISIS (International Satellite for Ionospheric Studies) satellites. Probes of this type were also carried on Tiros and Atmosphere Explorers A and B.

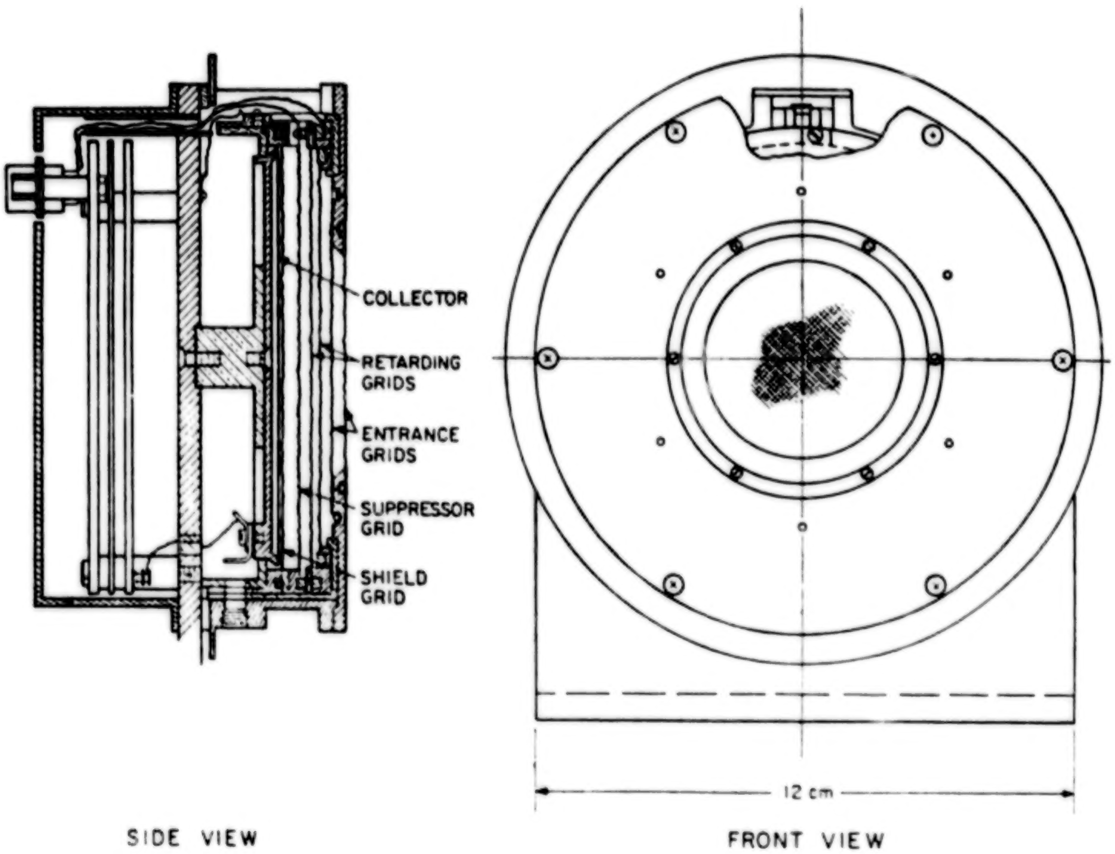

Figure 37. One of the sensor heads on a retarding potential analyzer (RPA) carried on board the Atmosphere Explorers.

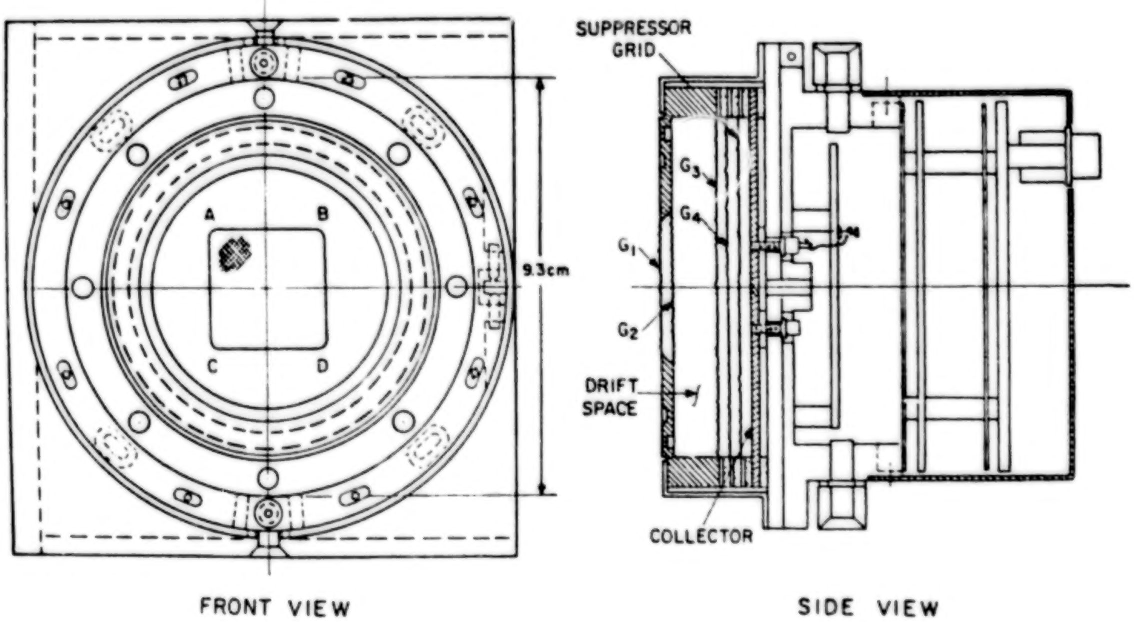

Figure 38. The ion drift meter (sensor head 4) measured the transverse drift velocities of ions.

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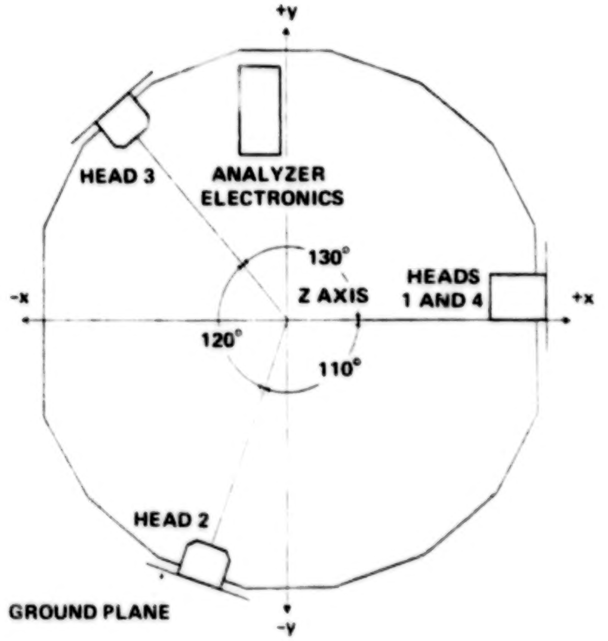


Figure 39. Locations of the four sensor heads around the spacecraft in a plane perpendicular to the spin axis.

Two long, thin cylindrical collectors protruded from the spacecraft into the surrounding plasma. The two collectors were independent to provide redundant measurements and thereby to prevent experiment errors. One probe was mounted parallel to the spacecraft's spin axis so that it would be perpendicular to the velocity vector at all times. The other was mounted radially from the spin axis so that it subtended all angles to the velocity vector with each spin of the spacecraft. Each probe consisted of a 10-cm long, 0.56-mm diameter collector extending beyond a 23-cm long guard electrode. Each sensor was spring-loaded to erect itself after the spacecraft's protective nose fairing was jettisoned following launch.

The probe measured the temperature and concentrations of electrons for use in studies of the thermal and particle balance of the thermosphere. The electron retarding potential region

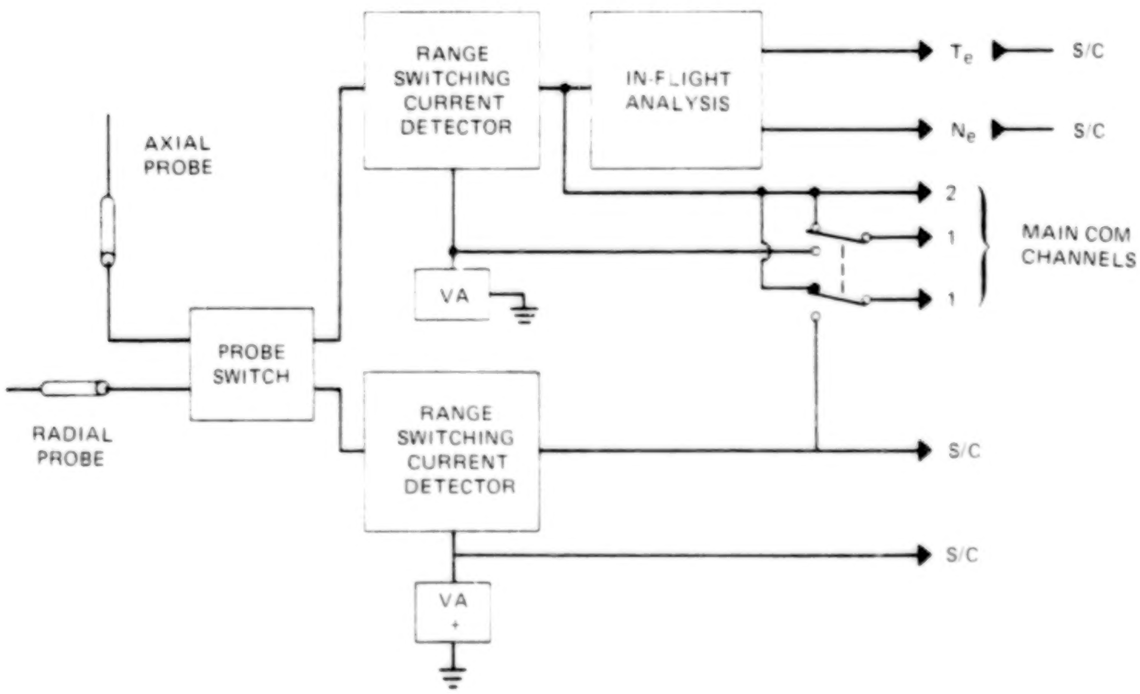


Figure 40. Block diagram of the main parts of the Langmuir probe (cylindrical electrostatic probe).

determined the electron temperature, and the electron attracting region determined the concentration of electrons. The collector potential was varied to vary the amplitude of the flux of thermal electrons into the probe.

An important improvement of the instrument over earlier models was the capability of the electronics that performed in-flight data analysis for temperature and density of electrons so that the value of these measurements could be telemetered directly. This considerably reduced the amount of data processing on the ground and made the results available more quickly.

Low-Energy Electron Spectrometer

The low-energy electron spectrometer (figures 41 and 42) was carried by Atmosphere Explorers C and D to monitor the energy input to the thermosphere from electrons in the 0.2- to 25-keV range. This instrument was designed to measure the flux of low-energy electrons that was expected along the orbit of the satellite, to determine the character of field-aligned currents in the auroral zone, and to study the precipitation of electrons from the magnetosphere during magnetic storms.

The detectors consisted of cylindrical electrostatic analyzers for species and energy selection, and Spiraltron electron multipliers as particle sensors. The instrument used on Atmosphere Explorer C contained three detectors; two of them measured electrons and ions from 0.2 to 25 keV in 16 logarithmically spaced steps, and one measured 5-keV electrons continuously.

The instrument for the D spacecraft contained 19 detectors, one ion-stepped energy analyzer, and two electron-stepped energy analyzers at two different angles for covering the energy range from 0.2 to 25 keV. In addition, this instrument contained 16 fixed-energy detectors

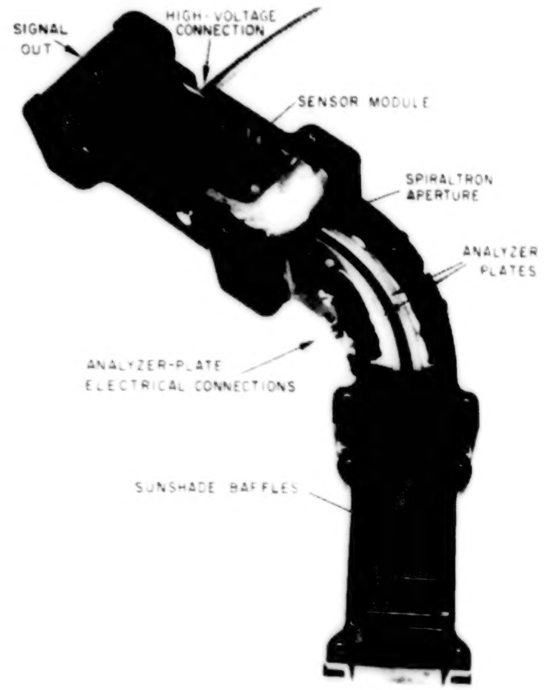


Figure 41. Low-energy electron analyzer, showing the sunshade, analyzer housing, and sensor.

for obtaining high time-resolution angular distributions in the spacecraft despun mode at five energies between 0.2 and 5 keV. The energies covered could be increased by 3.5 times by commands from the ground.

The distributions in energy were obtained by applying different fixed or stepped voltages to the electrostatic deflection plates of the individual detectors. Distributions in angle were measured by utilizing the spin of the spacecraft (in the spinning mode) and by mounting the detectors at various angles to the spacecraft's Y-axis for the one-revolution per orbit mode of operations.

Each detector package consisted of a sunshade, an analyzer, and a sensor module. All detectors were identical except that, in the instrument

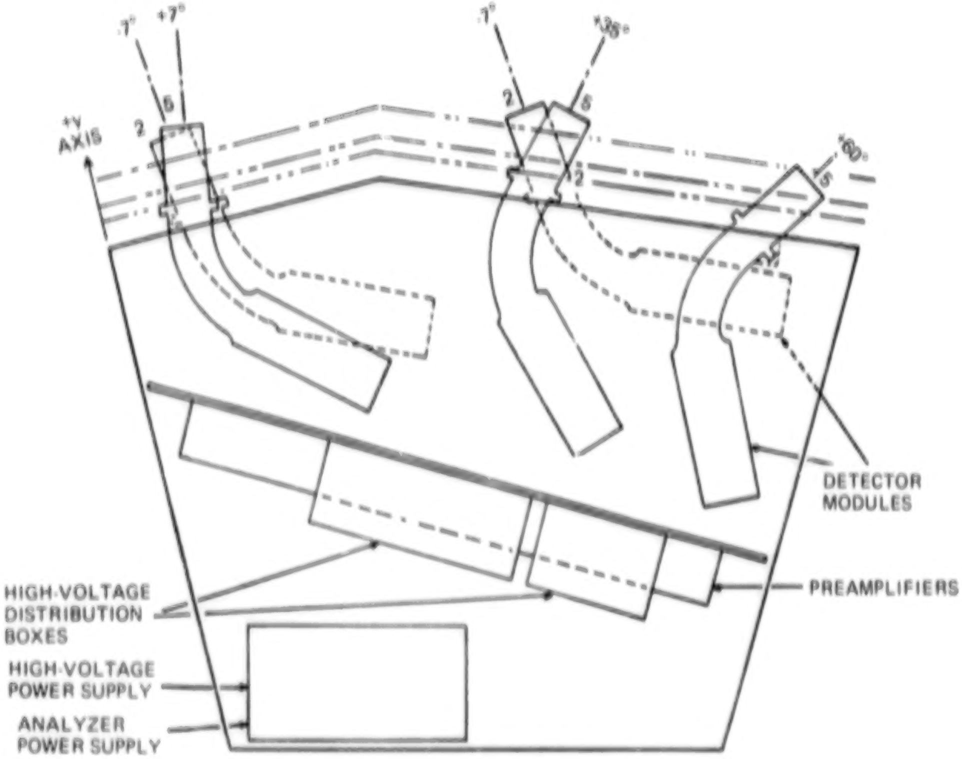


Figure 42. Orientation of the detectors and electronics in Atmosphere Explorer D. Several detectors were in each stack.

used on Atmosphere Explorer D. Spiraltrons with 1-mm circular apertures were used in the 12 lowest energy channels in place of the 1- by 6-mm entrances used on the other detectors.

The instrument could be operated in either of two modes. A monitor mode provided good energy resolution, moderate temporal resolution, and reduced pitch-angle measurements, with data acquisition simultaneous with the primary aeronomical and ionospheric measurements when the satellite was in either its spin or its despin mode. The data mode of the analyzer provided sufficient energy, pitch and angle, and temporal resolution to determine the character of the important electron beams encountered in the auroral and transauroral regions.

Photoelectron Spectrometer

The photoelectron spectrometer measured the intensity and energy distribution of the photoelectron flux in the thermosphere over a range of energies from 2 to 100 eV and precipitated electrons from 50 to 500 eV. This instrument provided the first high-resolution data on the energy spectra of atmospheric photoelectrons. Its energy resolution was 10 times better than that of any previous experiment. Among the important discoveries made by this instrument is the existence of photoionization peaks in the photoelectron flux.

The spectrometer used a 180-degree hemispherical electrostatic deflector coupled to an electron multiplier detector (figure 43 and 44). Apertures in the input and output focal plane

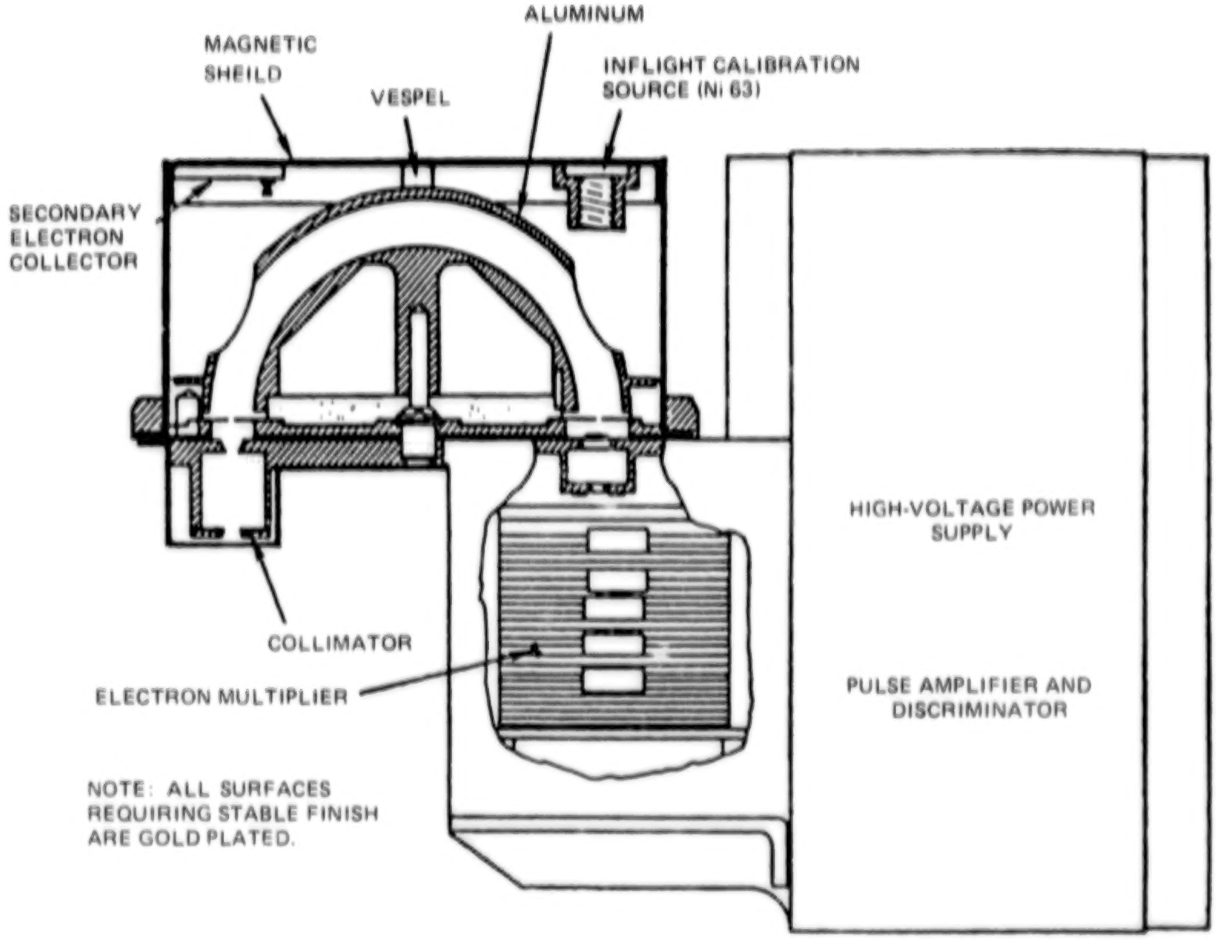


Figure 43. Cross section of the sensor head of the photoelectron spectrometer.

of the deflector provided field stops for the analyzer and established the resolution of the instrument. An additional larger aperture placed in front of the first analyzer defined the entrance port of the system. The first two apertures thus established the geometric factor for the analyzer (about 10^{-3} cm^2 steradians). A trap, placed behind the entrance aperture, caught high-energy particles and reduced the background from photoelectrons generated within the analyzer.

The photoelectron energy spectrum was scanned by sweeping the voltage between the two hemispherical deflection elements of the instrument, using a 1-second period exponential sweep voltage between the detectors. The differential electron energy spectrum was thus produced directly by the analyzer.

The spectrometer heads were placed on the spacecraft so that there was little shadowing of electron trajectories by the spacecraft or contamination of the spectra by photoelectrons generated by the Sun shining on the metal surfaces of the spacecraft.

Airglow Radiation

The Visual Airglow Experiment (figure 45), another portion of the science payload of the Atmosphere Explorers, was designed to measure

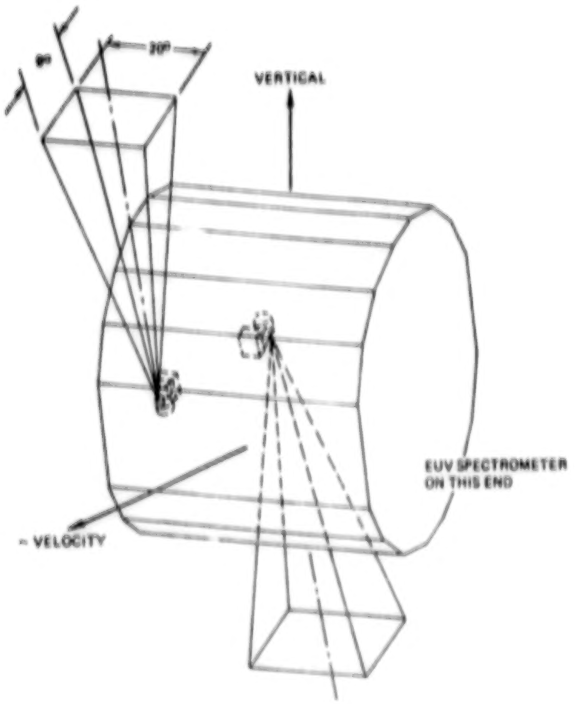


Figure 44. Orientations, look cones, and locations of the sensor heads on the Atmosphere Explorer AE-C and D spacecraft.

dayglow, aurora, and nightglow and to provide data on rates of excitation of atomic and molecular constituents of the thermosphere. The system was similar to one developed for the ISIS-B program. It used conventional filter photometers designed to monitor airglow and auroral-emission features in the spectral region between 2800 and 7320 A. Each Atmosphere Explorer measured six specific spectral lines and bands, including atomic nitrogen emission at 5200 A, the oxygen emissions at 5577 and 6300 A, and the oxygen ion emission at 7320 A.

The Visual Airglow Experiment had two distinct optical channels: a high sensitivity channel with a large field of view (3-degree half-angle cone), and a low sensitivity channel with a narrow field of view (3/4-degree half-cone). The narrow-angle channel was used to measure dayglow and nightglow horizons and to observe discrete auroral features that had strong spatial gradients. Each of the optical channels had a diameter of 2.3 cm, and they shared a filter wheel containing six filters, a dark position, and a calibration source of phosphor activated by radioactive promethiun 147.

Each optical system employed a combination of simple single-objective lens and field stop to define the angular field of view. The two channels were mounted at 90 degrees to each other, one looking tangential to the orbital path and the other looking perpendicular to it in the orbital plane.

Data from the Visual Airglow Experiment have been used to study the photochemistry and the energies of the thermosphere. In photochemistry studies, the Visual Airglow Experiment has played a key role in determining the importance of metastable atoms and ions in the thermosphere. Data from VAE have quantified much of the physics of these species, leading to a good understanding of the static state of the thermosphere and of its photochemistry.

Studies of the energetics of the thermosphere have led to a better understanding of the dynamic processes of the region. These studies included nonthermal transport of oxygen, morphology and theoretical modeling of the motion of metallic magnesium ions in the equatorial region, and low-latitude oxygen emissions and their relationship to meridional winds and electric fields.

The intensity of the airglow, measured by another instrument, was used to determine the amount of nitric oxide in the upper atmosphere.

Ultraviolet Nitric Oxide Spectrometer

The ultraviolet nitric oxide spectrometer was designed to provide profiles of nitric oxide

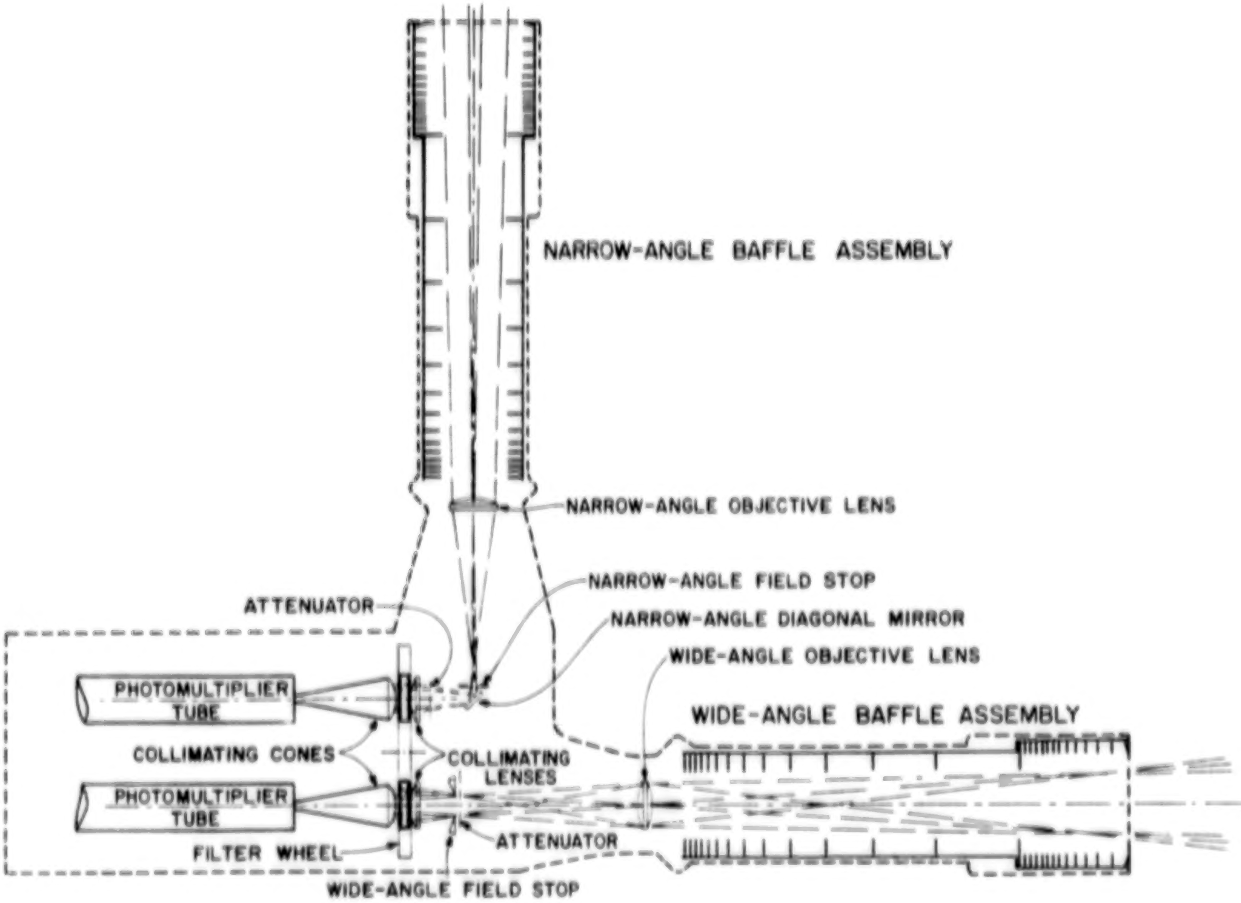


Figure 45. Optical schematic of the instrument used for observing the airglow from Atmosphere Explorer satellites.

density down to about 85 km by looking at the ultraviolet airglow emission of nitric oxide above the Earth's limb. The measurements obtained by this instrument combined the virtues of the near-instantaneous vertical probing of a sounding rocket with the diurnal, seasonal, and global coverage of a satellite.

The instrument (figure 46) consisted of a two-channel, fixed-grating, Ebert spectrometer that looked outward through the rim of the Atmosphere Explorer spacecraft. In the spinning mode, the instrument's field of view was repeatedly carried downward through the atmosphere Explorer spacecraft. In the spinning profiles of the intensity of the airglow. One of the channels operated at 2150 A to measure sunlight fluorescently scattered by nitric oxide. At lower altitudes, the signal was contaminated by Rayleigh-scattered sunlight; therefore, a second channel, which measured only the scattered light at 2190 A, was used to correct the signal from the first channel.

Because of the remote-sensing character of the spectrometer, measurements of nitric oxide were made at altitudes both above and below the perigee of the satellite. The range of altitudes encompassed the middle and lower thermosphere and the mesopause. The profiles were measured along the track of the satellite at all times when it was on the sunlit side of the Earth.

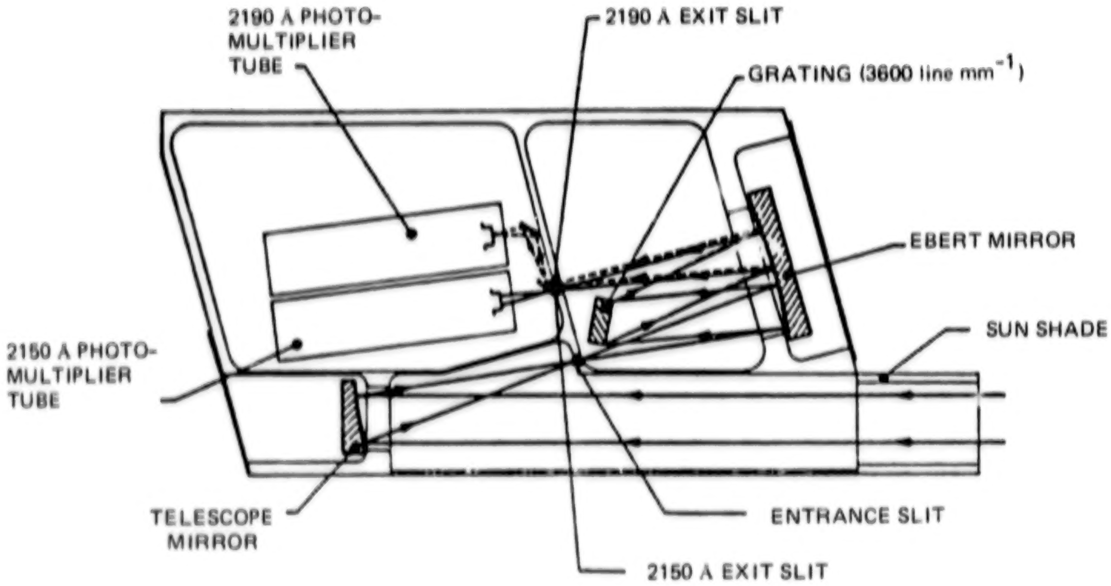


Figure 46. The ultraviolet nitric oxide spectrometer used ultraviolet airglow emissions from close to the limb of the Earth to measure the amounts of nitric oxide in the atmosphere.

The measurements were expected to provide valuable information about the sources, sinks, and transport of nitric oxide in the thermosphere, and when used in cooperation with other data from the spacecraft, would be important to investigations of thermospheric ion chemistry, the morphology of the turbopause, and auroral perturbations of the thermosphere.

Other Instruments

The spacecraft carried several other instruments. A set of sensors made engineering measurements so that the operation of the spacecraft and its payload could be evaluated from the ground. Pressure gages and accelerometers provided information for controlling orbit adjustments and evaluating the effects of drag on the spacecraft. In measuring the drag, the accelerometers also served the additional purpose, as described earlier in this chapter, of determining atmospheric density.

The Air Force provided two pressure gages as government-furnished equipment. One was a cold-cathode-type vacuum gage sensor with associated electronics. The sensor was a cylindrical unit mounted with its axis rotated 22.5 degrees from the X-axis of the spacecraft and its sensing aperture exposed to the airstream. This gage measured atmospheric density over an altitude range from 120 to 200 km to determine pressure.

The second pressure gage was a capacitance manometer, consisting of a sensor and its associated electronics, that measured pressure directly. The sensor had two inlet ports on each side of a diaphragm located 180 degrees apart so that either port could turn into the ram direction as the satellite spun. The gage was mounted so that the two inlet ports were perpendicular to the spin axis.

A planetary atmosphere composition test instrument (mass spectrometer) was flown on

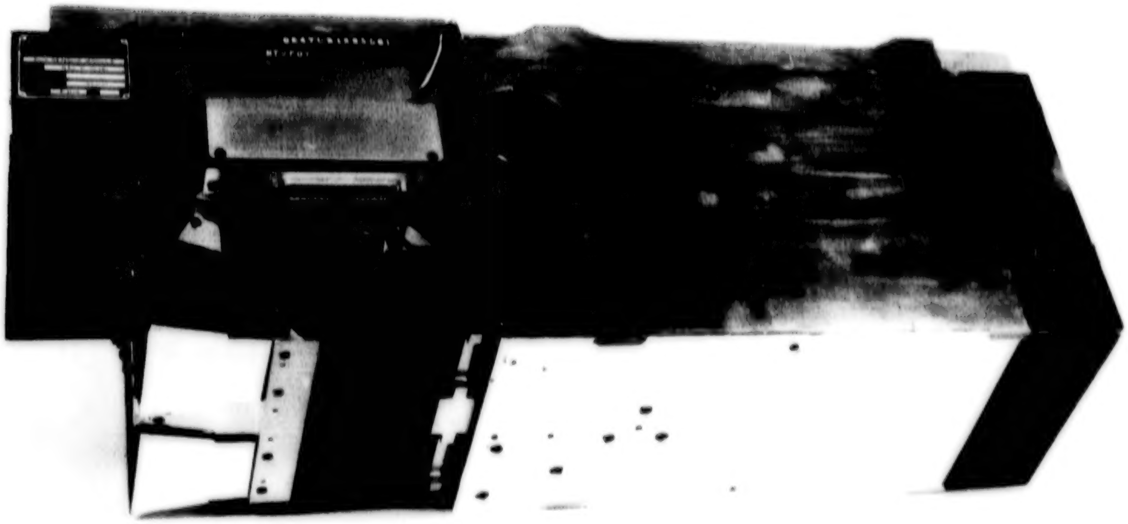
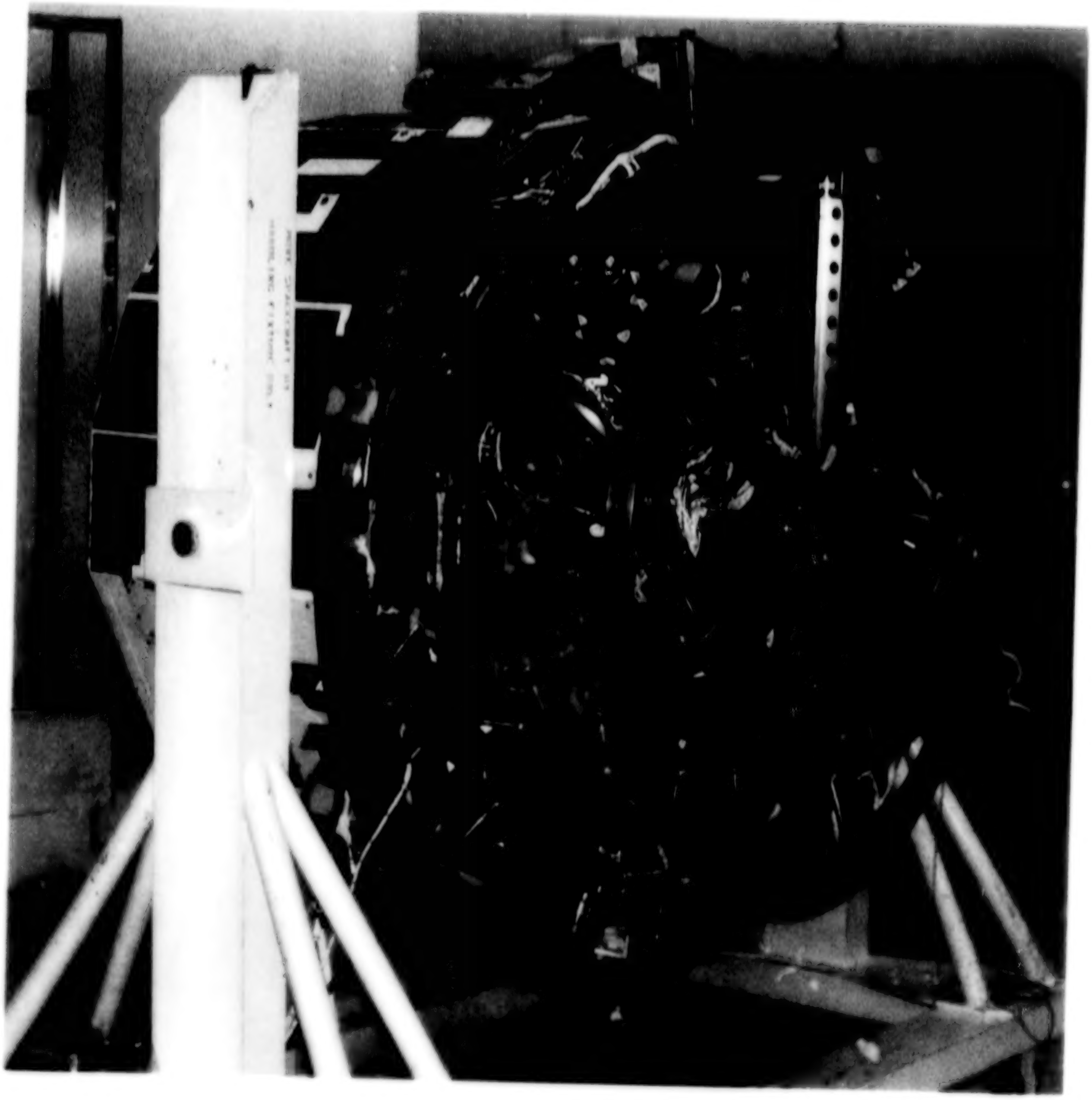


Figure 47. Backscatter Ultraviolet Experiment.

Atmosphere Explorer D to test the feasibility of making measurements of neutral particle composition from high-velocity planetary vehicles.

An instrument for measuring the effects of radiation on advanced electronic circuits was flown on Atmosphere Explorer E, which was expected to frequently travel through the Van Allen belts. A molecular return measurement unit was flown on Atmosphere Explorer D to check the effects on the measurements of the other science parameters of a contaminating gas (neon) ejected from the spacecraft. An energy analyzing spectrometer test was flown on Atmosphere Explorer E to provide number densities and species of ion mass in the ambient atmosphere by eliminating contributing effects of source gases close to the spacecraft and to other mass spectrometers. This instrument was a combination of a retarding potential analyzer, a neutral composition mass spectrometer, and a magnetic ion mass spectrometer.

A backscatter ultraviolet (BUV) instrument (figure 47) flown on Atmosphere Explorer E provided information on the amount of ultraviolet radiation reflected back from Earth toward space at 12 wavelengths from 2550 to 3400 A. Such measurements of the ultraviolet albedo of the Earth at the wavelengths that ozone absorbs, when compared with similar measurements made at a wavelength region relatively free from ozone absorption, permitted the investigators to calculate the total amount of ozone and the vertical distribution above its maximum amount up to approximately 55 km. The instrument, a spare from the Nimbus 7 program, consisted of a sensor module that used a tandem Ebert-Fastie double monochromator and an interference filter photometer channel. The fields of view of the photometer and the double monochromator were equal and colinear.



4

THE SPACECRAFT

Each of the Atmosphere Explorers approximated a short circular cylinder 135 cm in diameter and 115 cm high. The spacecraft and experiments weighed approximately 500 kg and were designed to minimize imbalancing torques created by atmospheric drag at the low point in orbit. Solar cells, mounted on the top and sides of the outer shell, supplied electrical power for the spacecraft and the experiments it carried. Various sensors and probes projected through the outer skin to collect data and to provide spacecraft attitude control information. The spacecraft were equipped with hydrazine thrusters for adjusting the orbit so that data could be collected over a range of orbits.

For the scientific instruments that it carried, the spacecraft provided a spinning platform in the orbital plane, a despun platform controlled to the local vertical, an initial power of 100 watts at 30-percent duty cycle, a minimum data storage capacity of 118 million bits, and a variable orbit capability. The general characteristics of the spacecraft were as follows:

- Launch Dates / Reentry

	Launch Dates	Reentry
AE-C	12/13/73	12/12/78
AE-D	10/06/75	3/12/76
AE-E	11/20/75	6/10/81

- Orbits
  Inclination: 19.5° – 90.1°
  Apogee: 3000 – 4300 km (initial)
  Perigee: ~157 km
  Period: ~132 min (initial)

- Design Life of Equipment: 12 months (min)

- Launch Vehicle: Delta

- Spacecraft Characteristics
  Weight: 665 kg ±10 percent (with propellant)
  Diameter: 137 cm max
  Projected area: 1.5 m^2 ±10 percent
  Plasma conduction surface: 0.6 m^2 (min)
  I_{spin}/I_{tumble}: 1.03 (min)

- Attitude Control
  Roll and yaw axes (orbit normal): 2° rms (circular)
  Pitch (spin) axis: ±1°
  Spin mode: 0.5 – 8 rpm ±1 percent
  Despin mode Earth-oriented: ±1°

- Power System
  Negative array
  N-on-P solar cells
  NiCd batteries
  Experiment bus: -24.5 volts

- Data
  Real time: 16,384 bps
  Record: 16,384 bps
  Playback: 131,072 bps
  Tape recorders (2): 236 million bits total

- Communications
  VHF tracking and real-time telemetry: 137 MHz
  S-band command and ranging (uplink): 2108.25 MHz

S-band telemetry and ranging (downlink): 2289.50 MHz

- Propulsion
  Propellant: Hydrazine
  Thrusters: 1.8 kg F
  Catalyst: Shell 405
  Propellant weight: 168 kg

- Thermal–Internal Temperature: 10° to 35°C (active with heaters as required)

- Scientific Instruments (typical)
  Volume: 0.25 m^3
  Baseplate area: 1.2 m^2
  Weight: 95 kg
  Power (initial): 112 watts
  On time nominal: 30 minutes
  Max: 120 minutes
  Duty cycle: 30 percent
  Commands: 496 (max)

DESIGN APPROACH AND EVOLUTION

In 1965, the small team of scientists and engineers interested in exploring the thermosphere and based at Goddard Space Flight Center began to consider the possibilities of using a spacecraft with propulsion capabilities to undertake a satellite mission into the lower thermosphere. The spacecraft would have to be stabilized, and it would have to penetrate deeply into the thermosphere while maintaining its orientation in orbit. Even with propulsion capabilities, the spacecraft would require a low ratio of area to mass. Problems to be solved included accurately locating the center of mass and the center of pressure so that aerodynamic imbalance would be as small as possible and the need to be able to change the spin rate of the spacecraft so that the spatial resolution of the measurements could be changed. This adjustment of the spin rate of a spacecraft was innovative. Actually, having the spacecraft despun to 1 RPO with the instrument looking forward in the direction of orbital motion would provide the greatest resolution, but such an orientation would not provide all the sensor orientation exposure needed for some experiments. Thus, the various science objectives could best be achieved by a spacecraft with an adjustable spin rate.

GENERAL STRUCTURE

The spacecraft structure consisted of reinforced platforms for mounting equipment, an adapter section for launch vehicle compatability, a number of reinforced handling and lifting pads, and the outer covers. The equipment platforms provided structural mounting surfaces for the outer shell, experiments, electronic packages, attitude control systems, hydrazine thruster subsystem, and the launch vehicle adapter.

Figure 48 shows a typical platform layout. The top of the outer shell provided a mounting surface for the solar cells and the telemetry antenna, as well as viewing ports for the solar-oriented experiment sensors. Solar cells were mounted on the outer shell to provide electrical power. Ports through which the experiments could be inspected before launch were located at several positions on the outer shell.

THERMAL SUBSYSTEM

Aerodynamic and solar heating in both the spin and despun modes of spacecraft operation contributed to the heat input. Active control of this thermal input was obtained by a set of thermally actuated louvers on the bottom of the spacecraft (figure 49), along with heat sinks, insulation, and insulation for confining the temperature of equipment within the spacecraft to a range of 10° to 35° C. Temperature sensors within the spacecraft controlled current flowing to bimetal activators that opened and closed the louvers. The propellant and the propulsion system were prevented from reaching too low an operating temperature by electrical heaters.

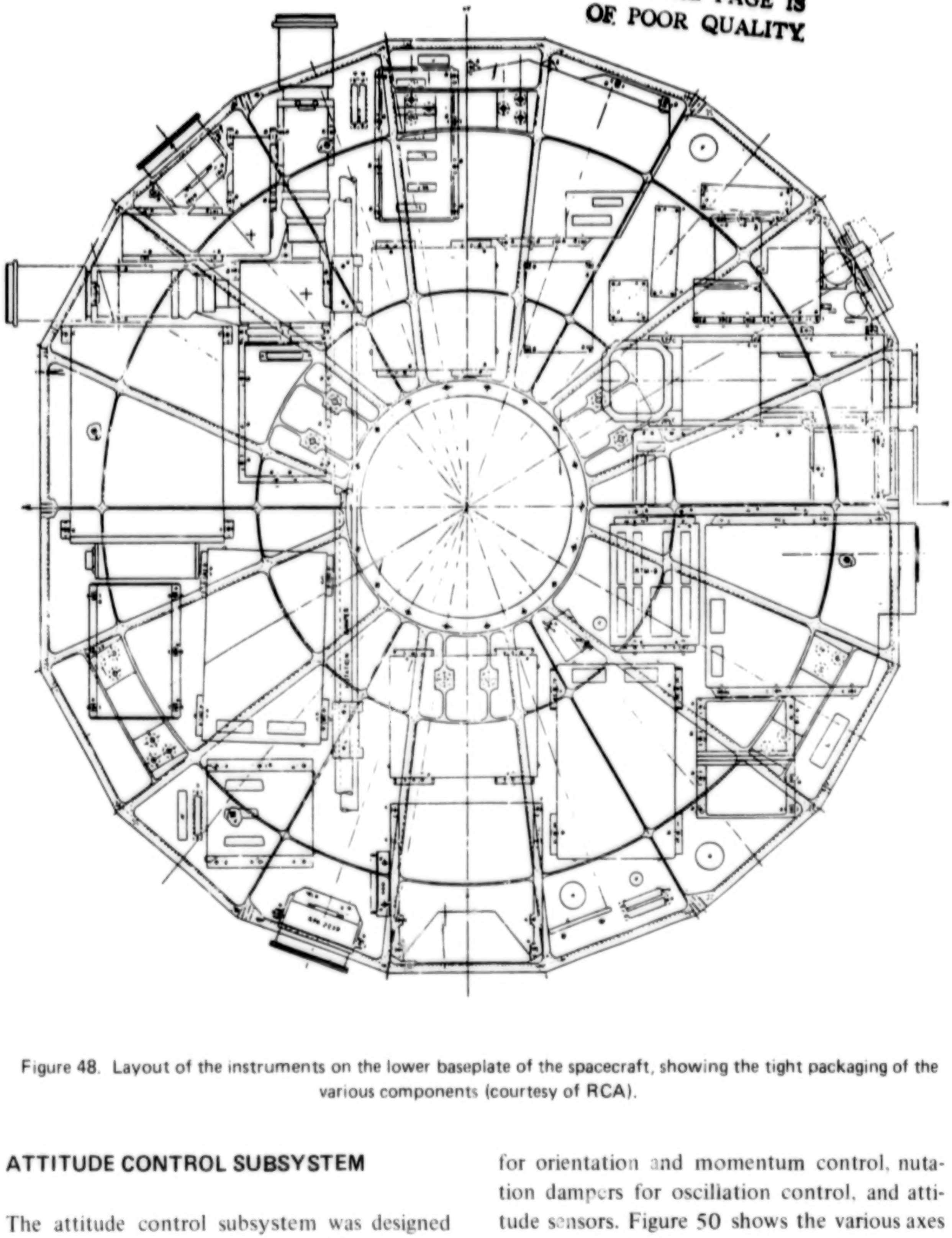


Figure 48. Layout of the instruments on the lower baseplate of the spacecraft, showing the tight packaging of the various components (courtesy of RCA).

ATTITUDE CONTROL SUBSYSTEM

The attitude control subsystem was designed for controlling the pointing of the spacecraft while in orbit. It used a momentum wheel for spinning body stabilization, magnetic torquers for orientation and momentum control, nutation dampers for oscillation control, and attitude sensors. Figure 50 shows the various axes of the spacecraft. The spacecraft had two modes of operation: the spin mode and the despun mode. In the spin mode, the spacecraft

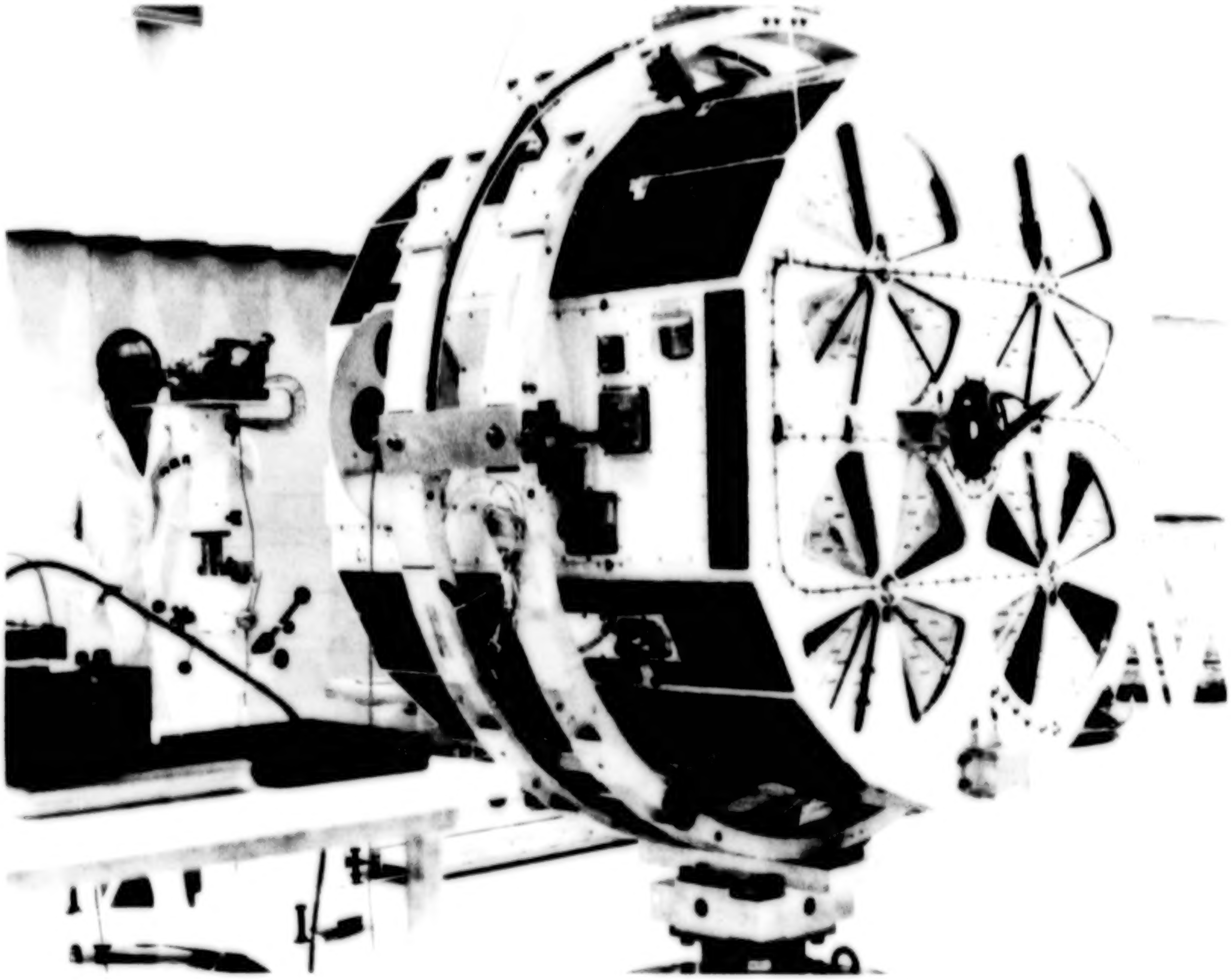


Figure 49. Barrel-shaped Atmosphere Explorer C undergoing alignment checks before shipment from the RCA plant to the Western Test Range. The circular end of the spacecraft toward the camera carries the thermal louvers. Projecting from its center is the rotating mirror (courtesy of RCA).

rotated about the polar, or Z-axis, which was normal to the orbital plane. The spin rate was variable by ground command from 0.5 to 8 revolutions per minute in 32 steps.

A fixed rate of 4 revolutions per minute, which was independent of the momentum and mass properties of the spacecraft, was also provided. This rate was initiated by ground command. In the despun mode, the spacecraft's Y-axis was aligned with the local vertical to permit the X-axis to point forward along the direction of the orbital path (the velocity vector) and with the spin axis (Z-axis) normal to the orbital plane. Ground commands could be used to select any of 360 settings for the despun mode, which permitted offset pointing for special experiments.

The momentum wheel provided a momentum reference for stabilizing the spacecraft and a reaction torquer for controlling the spin rate

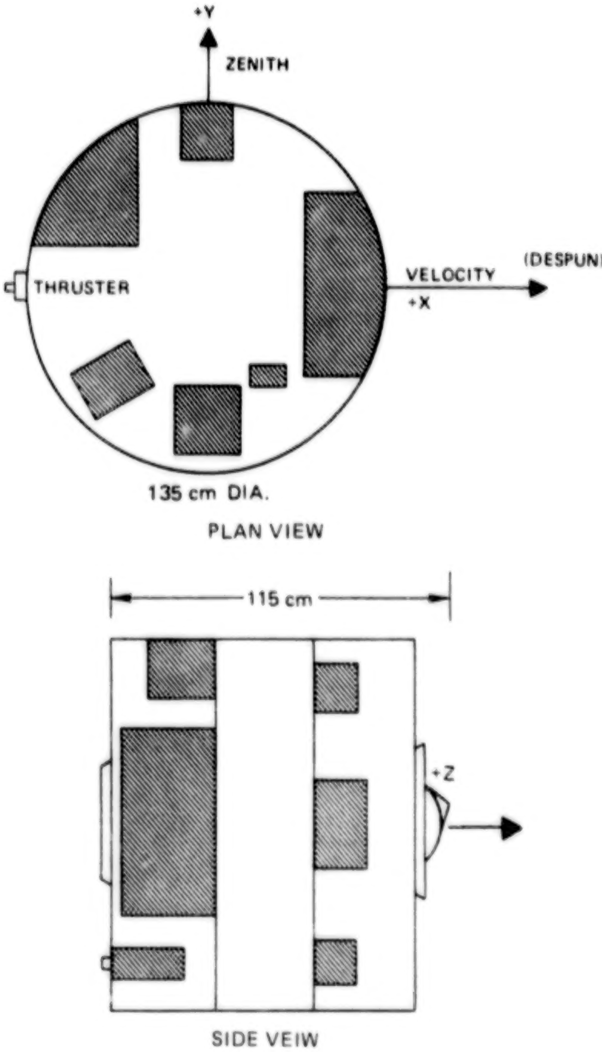


Figure 50. Orientation of the three main axes of the spacecraft. Each Atmosphere Explorer satellite was spun about its Z-axis.

and the despun attitude. The initial angular momentum was attained by spinning the spacecraft while it was attached to the Delta launch vehicle. A variable-speed drive motor then transferred the spacecraft's momentum to the wheel. Momentum was then shared as required by appropriate transfers between the spacecraft and the wheel. In the despun mode, essentially all the momentum was transferred to the wheel from the spacecraft; in the spin mode, it was distributed between the wheel and the spacecraft. The spin rate was controlled to the commanded rate by sensing the rotation rate with respect to the local vertical and then controlling the speed of the wheel accordingly.

Magnetic torques were used to control the spacecraft's orientation and momentum magnitude. Horizon sensing determined the orientation. A magnetic precession torque applied to the spin axis aligned the axis normal to the orbital plane. An automatic controller generated the magnetic torques, which were also controlled by ground command if needed. Magnetic torque applied about the spin axis controlled momentum magnitude. By appropriately switching the magnetic field of a control coil, an interaction with the Earth's magnetic field could produce a desired change in angular momentum.

Passive nutation dampers on the despun portion of the spacecraft damped spacecraft oscillations caused by separation of the launch vehicle and those caused by aerodynamic drag, firing of the thrusters, and other disturbing forces.

The attitude sensors for determining the attitude of the spacecraft consisted of infrared horizon scanners and a solar aspect sensor. The horizon scanner measured the deviation of the Y-axis from the local vertical in the despun mode, and the spin rate in the spin mode. In the despun mode, the scanners provided position errors from 120- to 4000-km altitude for both a standard and an inverted position. Positioning accuracy was sufficient for meeting the requirement of the attitude errors permitted for the spacecraft. In the spin mode, the spin had to be kept within 5 percent of the rate commanded, and in the despun mode, the Y-axis had to be aligned to within 2 degrees of the local vertical about the Z-axis, which had to be normal to within 2 degrees of the orbital plane. The total momentum of the wheel and spacecraft had to be maintained within 10 percent of the average momentum.

ORBIT-ADJUST PROPULSION SYSTEM

The orbit-adjust propulsion system made use of two hydrazine thrusters for adjusting perigee and apogee altitudes and one offset thruster for providing yaw torque maneuver capability. The thrusters were usually fired in the despun mode in either the standard or inverted position of the spacecraft to increase or decrease orbital velocity as required to change the orbit. The yaw maneuver was performed at a 90-degree position in the despun mode.

Two main thrusters developed 1.8-kg thrust each. The spacecraft carried 168 kg of propellant, which was sufficient for a total velocity change of 610 meters per second. The thrusters were located opposite the forward-pointing experiments. The velocity change thrusters were aligned so that their thrust line coincided with the center of gravity of the spacecraft. A third yaw thruster was offset 17 degrees from the center of mass. Propellant consumption did not significantly affect the center of mass because of the arrangement of the propellant tanks, which were symmetrically located with respect to the center of the spacecraft.

Propellants were stored in six cono-spherical tanks, each of which contained a metal reversing diaphragm to separate the propellant from the nitrogen gas that expelled it from the tank. This design also maintained a balanced flow so that the center of mass of the spacecraft remained undisturbed.

POWER SUBSYSTEM

Power for the spacecraft was supplied by a solar array and stored in three 6.0-ampere-hour nickel-cadmium batteries. An associated power distribution unit, chargers, power regulators, and converters were used for control. Each battery was charged from the solar cells through a separate charge controller.

The solar array of 10,000 cells covered the top and sides of the spacecraft (figure 51) and generated 160 watts. The unregulated spacecraft bus voltage of -26 to 38.5 volts was consistent with the design of the subsystems and suitable for the experiment bus voltage of a regulated -24.5 volts.

Power available for the payload at the beginning of the spacecraft's mission was 100 watts at a 30-percent duty cycle. At least once a day, the power could be 100 watts continuous for 60 minutes. Every third day, it was 100 watts continuous for 120 minutes in lieu of the 60-minute period. Because of degradation of the solar cells in orbit, the power supplied to the payload after 1 year was only at a 15-percent duty cycle but still 100 watts.

COMMUNICATIONS AND DATA HANDLING

The communications and data handling subsystems for the Atmosphere Explorers consisted of telemetry, tracking, command and control, and the antennas. The telemetering system for the payload and spacecraft data used redundant encoders, spacecraft clocks, tape recorders, and VHF and S-band transmitters.

The encoders converted analog and digital science and engineering data into a uniform stream of information at a rate of 16,384 bits per second. This information stream was sent to tape recorders on the spacecraft or to transmitters for relay to Earth. Each encoder contained a main frame of 128 8-bit words. The spacecraft clock provided accurate time information in binary code for the telemetry data. The clock ran continuously from launch and repeated after 1.5 years. Redundant tape recorders provided a remote recording capability for 118 million bits of data. The recording rate was the 16,384 bits per second; the playback rate was 131,072 bits per second.

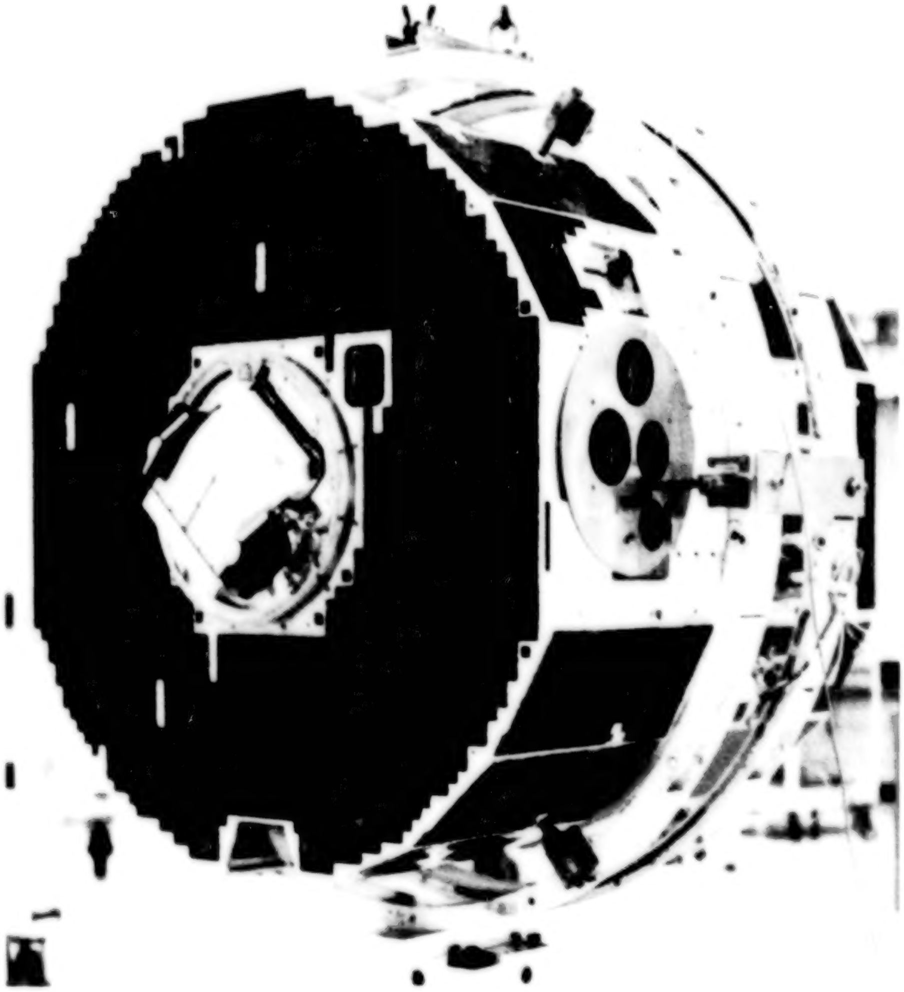


Figure 51. Atmosphere Explorer C, showing the solar cells on the circular end-plate opposite to that carrying the louvers (courtesy of RCA).

Redundant transponders provided S-band telemetry for tape recorder playback and for real-time telemetry. The output at 2289.5 MHz was approximately 4.3 watts of radiated power in the high-power mode and 0.5 watts in the low-power mode. The transmitter turned on automatically on receipt of an uplink signal from the ground. Redundant VHF transmitters sent real-time telemetered data with a radiated power of 1 watt at 137.23 MHz. The 0.25-watt carrier of these transmitters served as a beacon for tracking the spacecraft.

The S-band transponder received commands from the ground to the spacecraft at 2108.25 MHz. Passage of the spacecraft through the lower thermosphere and the consequent apogee changes resulting from drag required orbital update data via this command system on a short-term continuing basis.

COMMAND AND CONTROL

The spacecraft was commanded by a PCM instruction command system. The spacecraft

system consisted of redundant S-band FM transponders and command decoders that were capable of decoding about 496 commands. Commands were implemented by automated programmers aboard the spacecraft that could remotely control the turnon of the spacecraft, of the individual instruments, and the tape recorder, real-time operations, and the despun mode. With a single command, they could vary the delay time to spacecraft and instrument turnon by up to 76 hours in 4-second increments.

An omnidirectional whip antenna was provided for the VHF telemetry and beacon signals. An omnidirectional S-band resonant cavity, slot-type, belt antenna around the equator of the spacecraft provided for S-band telemetry, command, and tracking.

LAUNCH VEHICLES

The first Atmosphere Explorers, A and B, were launched by a Delta launch vehicle. Its first stage was a McDonnell Douglas Astronautics Corporation DM-21 Thor, a 17.4-meter liquid-propellant rocket that generated 77,000-kg thrust over a burning time of 2 minutes and 25 seconds. The second stage was an Aerojet-General Corporation liquid-propellant rocket that developed 3400 kg thrust for about 160 seconds. A third stage consisted of an NPP-X-248 solid-propellant motor that developed 1360 kg of thrust for about 40 seconds.

Atmosphere Explorer B experienced excessive propulsion on this launch vehicle because radio guidance was lost during launch. The second stage, which had a reserve of 8 seconds of thrust, actually burned all its propellant. The spacecraft was going too fast. To obtain the desired orbital inclination of 63.5 degrees, the final stage had to be fired almost vertically. Although this produced an orbit with a precession rate that led to the required inclination, the apogee of the orbit was more than twice that desired—2600 km rather than 1200 km.

For the new series of Atmosphere Explorers (C, D, and E), improved Delta launch vehicles were available. For Atmosphere Explorer C, the two-stage Delta 1900 launch vehicle was used. It had an overall length of approximately 22 meters and a nominal launch weight of 100,000 kg.

The first stage was a McDonnell Douglas modified Thor booster that incorporated nine strap-on Thiokol solid-propellant rocket motors. The booster engine was a Rocketdyne liquid-oxygen/liquid-hydrocarbon unit that was gimbal-mounted to provide pitch and yaw control. Two small liquid-propellant engines provided roll control and later pitch and yaw control after the main engine had been cut off at the end of its scheduled period of thrust. The second stage was powered by an Aerojet-General gimbal-mounted liquid-propellant engine.

Atmosphere Explorers D and E were launched by the improved two-stage Delta 2910 launch vehicle. Its overall length was about 35 meters. The first stage was a modified Thor booster that incorporated nine strap-on solid-propellant rocket motors, and the second stage was a liquid-propellant rocket.

These new boosters were precise in injecting their payloads into orbit. They made the Atmosphere Explorer mission possible because the satellites could be placed much more precisely in the required orbits, particularly with regard to perigee. All were placed in initial orbits with perigees and apogees very close to the required altitudes.

C-2

ORIGINAL PAGE
COLOR PHOTOGRAPH

5

FROM CONCEPT TO EXPLORATION

Preliminary design review of the Atmosphere Explorers (AE's) took place in February 1972, followed by mission objective reviews for C in August 1973 and for D and E in September 1975.

Launch of Atmosphere Explorer C was scheduled for October 1973. The spacecraft was actually launched on December 16, about 45 days late. Although the delay was partially caused by a higher priority ITOS-F launch, other problems were contributing factors. The spacecraft was going through prelaunch checkouts at the Vandenberg Air Force Base hanger complex (AE-C was launched from the Western Test Range near Lompoc, California) when engineers discovered that the Z-axis was not aligned as required. The spacecraft had to be partially disassembled and the axis adjusted by inserting weights in crevices on the top and bottom of each baseplate to bring the spacecraft center of mass to within 0.13 cm of the ideal location.

During the later stage of development in the summer of 1973, questions arose as to the capability of the spacecraft to resist nutation because the momentum wheel rotated on a single bearing. Evidence from the Tiros-M launches had indicated that there might be a damping problem with the momentum wheel of Atmosphere Explorer. Therefore, the engineers obtained a pendulum damper of the type used in the Orbiting Solar Observatories and modified it to cover the range from 0 to 4 rpm, tuning it to two different frequencies to provide high damping at small angles. The damper was placed in the spacecraft, and the engineers believed that it would solve any nutation problems arising from the single bearing.

An aerodynamic fairing or protective shroud protects the spacecraft from the Earth's atmosphere during the ascent of the booster rocket. The night before this protective shroud was placed around the spacecraft, the project manager, David Grimes, was making his final inspection. The thermal louvers were moved so that the interior of the spacecraft could be seen. Grimes was astounded to see that the pendulum damper had been placed backward in the spacecraft. It turned out that the damper had initially been placed correctly within the spacecraft with the pendulum ball to the inside. An engineer checking the spacecraft had seen this and reversed the damper because that would have been the normal way to install such a device. However, it had been designed so that the spring would relax at 4 revolutions per minute and not extend as might have been believed.

Nevertheless, Grimes decided to let the spacecraft fly as it was because it would have been time-consuming to take it apart and correct the damper. The decision was based on the fact that it would work as it was at 1 rpm and the higher rate might not be needed. When the spacecraft achieved orbit, it demonstrated that

the nutation *could* be controlled by putting all the spin into the wheel and then gradually increasing the despin rate of the body of the spacecraft. In fact, the damper did not have to be used.

In Atmosphere Explorer D, a damper was installed in the correct orientation and was used in orbit because in this case the single bearing approach caused the anticipated problem.

For the E spacecraft, a damper tuned to 4 rpm was required. All the machine shops and machinists available to the contractor, Ball Brothers in Boulder, Colorado, had to be marshalled to build a qualified damper in only 7 days by working round the clock. Quick studies showed that the damper could be mounted on the top base plate, but this would require some compromise on the positioning of the cosmic radiation environment package. In fact, the damper had to be placed on top of the radiation package, and its alignment was critical to within a few minutes of arc. Nevertheless, the damper was installed without delaying the launch. It was ironical that, after launch, only one of the dampers was actually needed and it was not the one that had to be mounted so hurriedly just before liftoff.

Another big challenge in developing the spacecraft involved the propellant tanks for the onboard thrusters needed to maintain the orbit. Six tanks were spaced uniformly around the spacecraft figure axis (figure 52). These tanks had to be designed so that propellant use would not disturb the center of mass of the spacecraft and thereby lead to unacceptable aerodynamic torques as the spacecraft rushed through the atmosphere at the low point of its orbit.

The design for the tanks separated the propellant from the nitrogen pressurizing gas by a metal diaphragm. Intensive studies determined the manufacturing requirement for the diaphragms, and work was continuing to develop reliable diaphragms as late as the spring before the first launch. The design was for a truncated cone of stainless steel with stainless steel rings so that the cone could fold at the rings. The basic problem encountered involved cracks that occurred at the welds when the diaphragm was recycled during tests.

In one such test, the mechanical test model of the spacecraft was shaken on a vibrating table to simulate the launch environment. Three of the propellant tanks were loaded with water, and the other three tanks were dummies. After the test, the test engineer brought a bottle of murky water to David Grimes. The bottle bore mute testimony that the diaphragms had cracked under the vibration.

It was discovered that the diaphragms could be subjected safely to one cycle of operation without failing, but more than one cycle would lead to failure. Therefore, the decision was made to fly the spacecraft with diaphragms that had not been put through the test cycle. Great care was taken during manufacture, and the diaphragm was flexed only once by the loading of the propellant. A gas analyzer on the nitrogen side of the diaphragm monitored whether any of the hydrazine passed through the diaphragm during loading. If none was detected, engineers knew that the first flexing had been successful. A minor crack would not have been a problem because the surface tension of the propellant would have kept it within the tank. For all three flights, the tanks worked properly.

Spacecraft integration and spacecraft environment testing were completed as follows: AE-C, August and October 1973; AE-D, November 1974 and January 1975; and AE-E, August and September 1975.

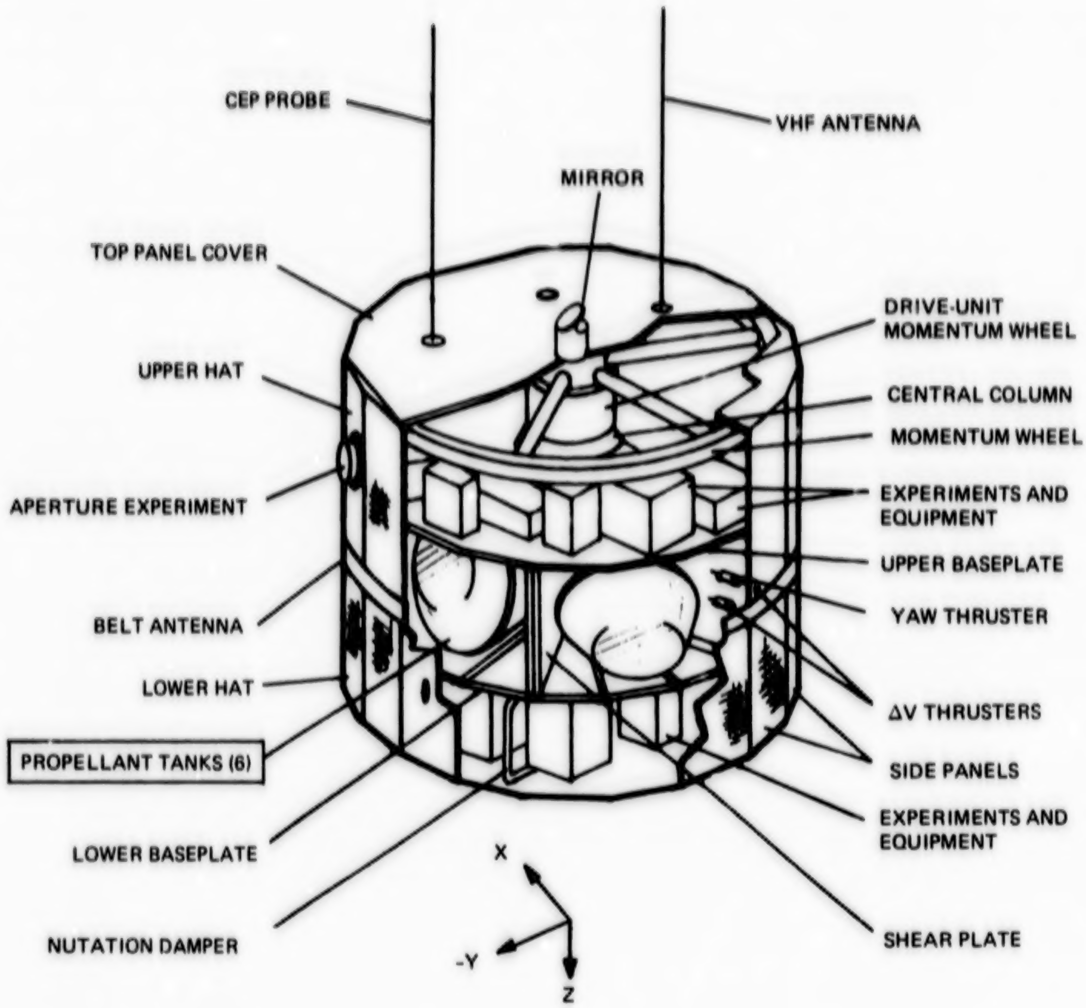


Figure 52. Cutaway view of the Atmosphere Explorer, showing two of the six propellant tanks.

In developing instruments for the low perigee passes of Atmosphere Explorers, investigators incorporated some special features in their instrumentation. For example, the closed-source, neutral-mass spectrometer was equipped with a commutator that had a high sampling rate so that it could make routine measurements of the electron current to the accelerator, the ion repeller, and the electrodes for the anode of the ion source. The commutator also permitted sampling of the temperature of the ion source and of the antechamber, both of which would respond to the aerodynamic heating encountered at low altitudes and could affect the measurements made in the lower thermosphere.

In the closed-source neutral-mass spectrometer, there was concern that there might be contamination by gas from the hydrazine thrusters which could cause degradation of the internal surfaces of the sensors. The solution was to provide the instrument with a cover arm on a rotary solenoid. When this solenoid was energized, a cover obstructed the orifice of the instrument's antechamber so that thruster gases could not enter it.

A special design of the visible airglow photometer was developed to prevent degradation or failure of the detectors if light from a bright source such as the Sun or the sunlit Earth's surface should enter the instrument. A "squinting" technique was developed whereby, when the light reaching the detectors reached a preset safety level, the bias voltage of the cathode was reversed within 1 millisecond. The voltage was then slowly allowed to return to a normal value. As it did so, the light reaching the detectors was monitored, and if it again reached the limit, the bias immediately returned to the safe level.

Another example of new scientific instrument development for Atmosphere Explorer involved the use of the Langmuir probe at low altitudes. These probes had been used in laboratories and in sounding rockets since the early flights of such rockets. It was believed that, deep in the atmosphere, electron temperature would be much lower than that encountered by satellites that did not dip below 250 km where the temperature was above 1000 K. It was calculated that, at 120 km, the Atmosphere Explorers might encounter electron temperatures of 300 to 400 K. These temperatures would be difficult to measure with a Langmuir probe because such temperatures represent low-energy electrons, and measuring them would require great surface uniformity in the tungsten collector.

The investigators settled on a technique for vapor-deposited metal surfaces that had been successfully demonstrated in a laboratory. This technique provided for crystal growth on the surface of the collector, so that the entire surface was, in effect, one tungsten crystal rather than a polycrystal mix. Without such an approach, the three normal metallic faces of the crystals would have led to differences of approximately 100 millivolts, which was more than the equivalent energy of the electrons that the probe would be detecting, and the measurements would have been smeared.

Laboratory demonstrations indicated that a probe could be made with a uniformity of surface within a few millivolts. The problem then became one of making such a surface in the form of a cylinder. This problem was solved by Ultramet of California, a company that has specialized in growing single crystals on the surfaces of various shapes.

Another expected problem was the contamination of the surfaces because they are electrical conductors and must make contact with the plasma of the thermosphere. The spacecraft would periodically fire its thrusters to maintain orbit, and it was believed that the exhaust from the thrusters might adhere to the surfaces and form a layer that would prevent good electrical contact with the plasma at the low electron energies involved. The investigators guarded against this problem by building heaters into the collectors so that they could be heated to a temperature of 600 degrees C, which would be sufficient to drive off any thruster gas residue. When Atmosphere Explorer C was flown, the investigators were pleased to find that the thruster exhaust did not cause any problems. When they tested the effects of the heaters well into the mission, no effects were measurable, and it was concluded that contamination from thruster exhaust did not present a problem.

Another major effort before launch involved Atmosphere Explorer E, which was to be launched soon after the report that fluorocarbons might destroy the protective ozone layer in the upper atmosphere. In late fall of 1974, it was suggested that an ozone-measuring instrument might be flown on AE-E (figure 53). David Grimes contacted Donald Heath, an AE experimenter using back-scatter ultraviolet instrumentation on other programs, to determine if he might have an instrument for this purpose that could be used on AE-E, similar to the experiment that had been flown on Nimbus 4. Heath said that he had such an instrument but that it was being reconfigured

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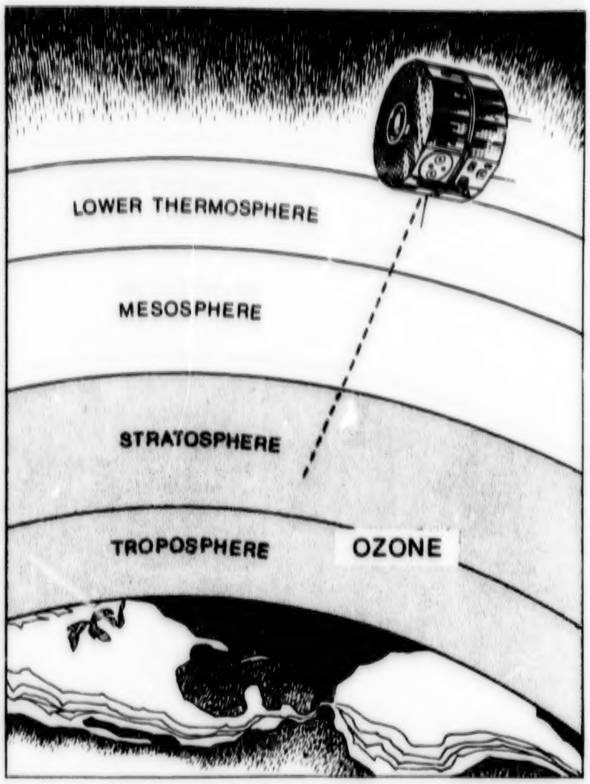

Figure 53. Artist's impression of how Atmosphere Explorer E used one of its instruments to take systematic readings of the ozone layer of the stratosphere (courtesy of RCA).

for a balloon flight and had been taken apart. A proposal was quickly written and accepted by NASA Headquarters. Engineers rearranged the upper deck of AE-E, and the backscatter ultraviolet instrument was included in the complement of instruments for the satellite (figure 54). Being very large, it required a lot of space, but the engineers were able to rearrange the upper deck and still fly all the original payload on schedule.

All experiments were developed and completed for AE-C by April 1973, for AE-D by September 1974, and for AE-E by February 1975.

After flight acceptance tests at the contractor's plant, each spacecraft was shipped to the launch site to be mated with its launch vehicle and tested further. At Kennedy Space Center, the spacecraft were checked in specialized facilities. The capability of the Delta launch vehicle to spin up the spacecraft before separation was tested there, too. Similar tests were performed at the Western Test Range for the spacecraft launched from the West Coast (figure 55).

Flight readiness reviews were made at the beginning of November 1973 for AE-C, in March 1975 for AE-D, and in December 1975 for AE-E. Each spacecraft in turn was mated to its launch vehicle, and its protective nose fairing was installed (figure 56). Finally, the big rocket booster, with its precious cargo, was readied on the launch pad for firing (figure 57). All three spacecraft were successfully launched: AE-C on December 13, 1973, AE-D on October 6, 1975, and AE-E on November 20, 1975. The characteristics of their initial orbits are shown in table 4.

Table 4
Initial Orbits of Atmosphere Explorers

Spacecraft	Launch Date	Perigee (km)	Apogee (km)	Inclination (degrees)	Period (minutes)
A	April 2, 1963	254	915	57.6	96.4
B	May 25, 1966	257	2257	64.7	110.0
C	December 13, 1973	154	4300	68.1	132.4
D	October 6, 1975	154	3816	90.1	126.9
E	November 20, 1975	157	3025	19.7	118.0

ORBIT PHASES

When the spacecraft had successfully reached orbit, their subsequent operation consisted of three phases: early orbit, elliptical orbit, and circular orbit.

The early orbit phase took place from the time of orbit insertion through the first month of

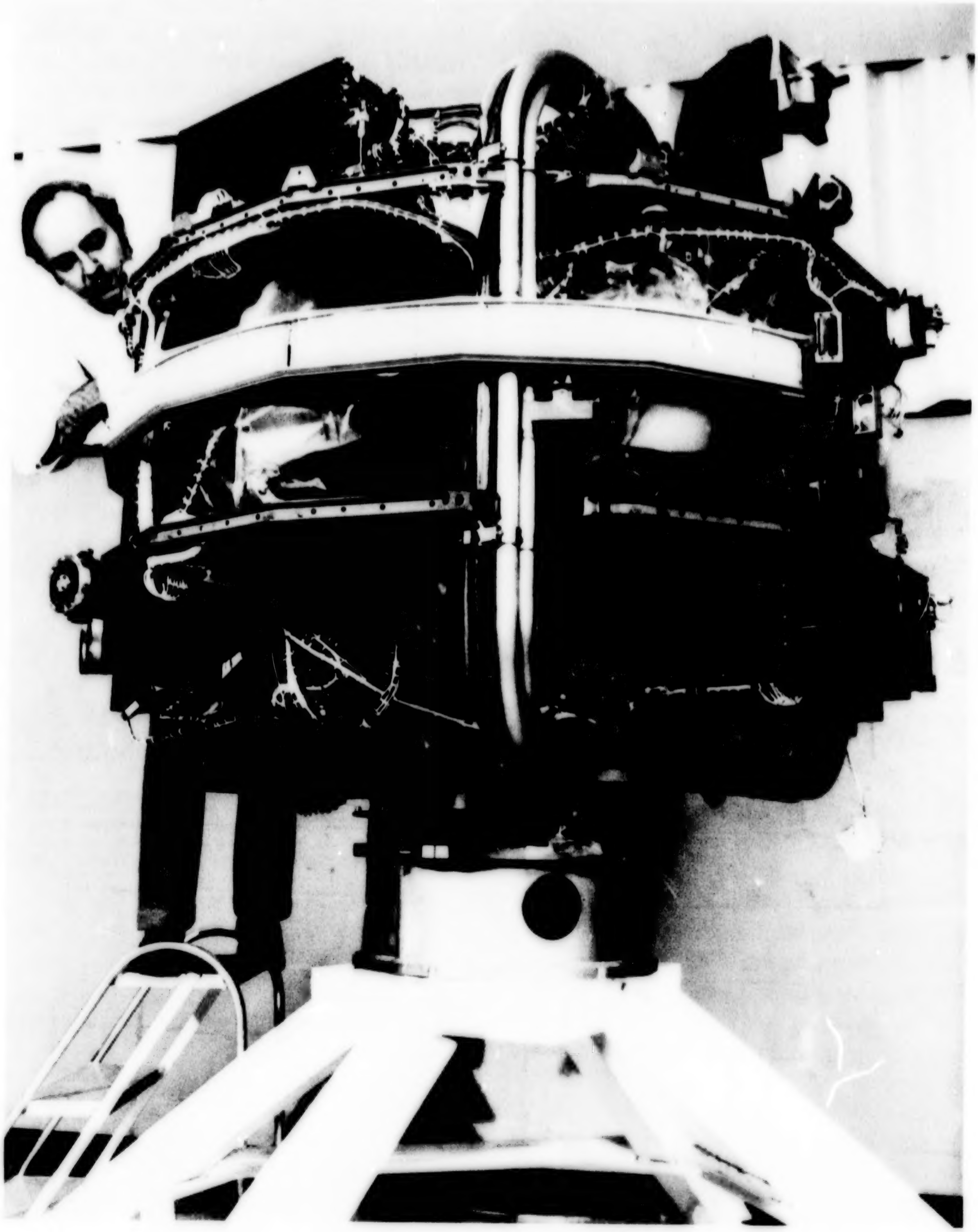

Figure 54. RCA technician, Ernest Toth, installs the backscatter ultraviolet (ozone sounding) instrument on Atmosphere Explorer E.

Figure 55. Engineers inspecting Atmosphere Explorer D in preparation for its launch into polar orbit from the Western Test Range by a Thor/Delta rocket.

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Figure 56. Approaching final preparations before launch, the satellite is mated with the launch vehicle, and half of the protective nose fairing is in place.

the mission. During this phase, real-time telemetry data from the satellite were processed to provide information on the status of instruments, verifications of commands issued to the spacecraft, and critical information about the way the spacecraft was performing in general. For example, during orbital maneuvers, the tracking stations sent tracking data as received to the Goddard Space Flight Center for use in computing the orbit to determine if further adjustments were needed following a maneuver. The operating plan for the solar ultraviolet

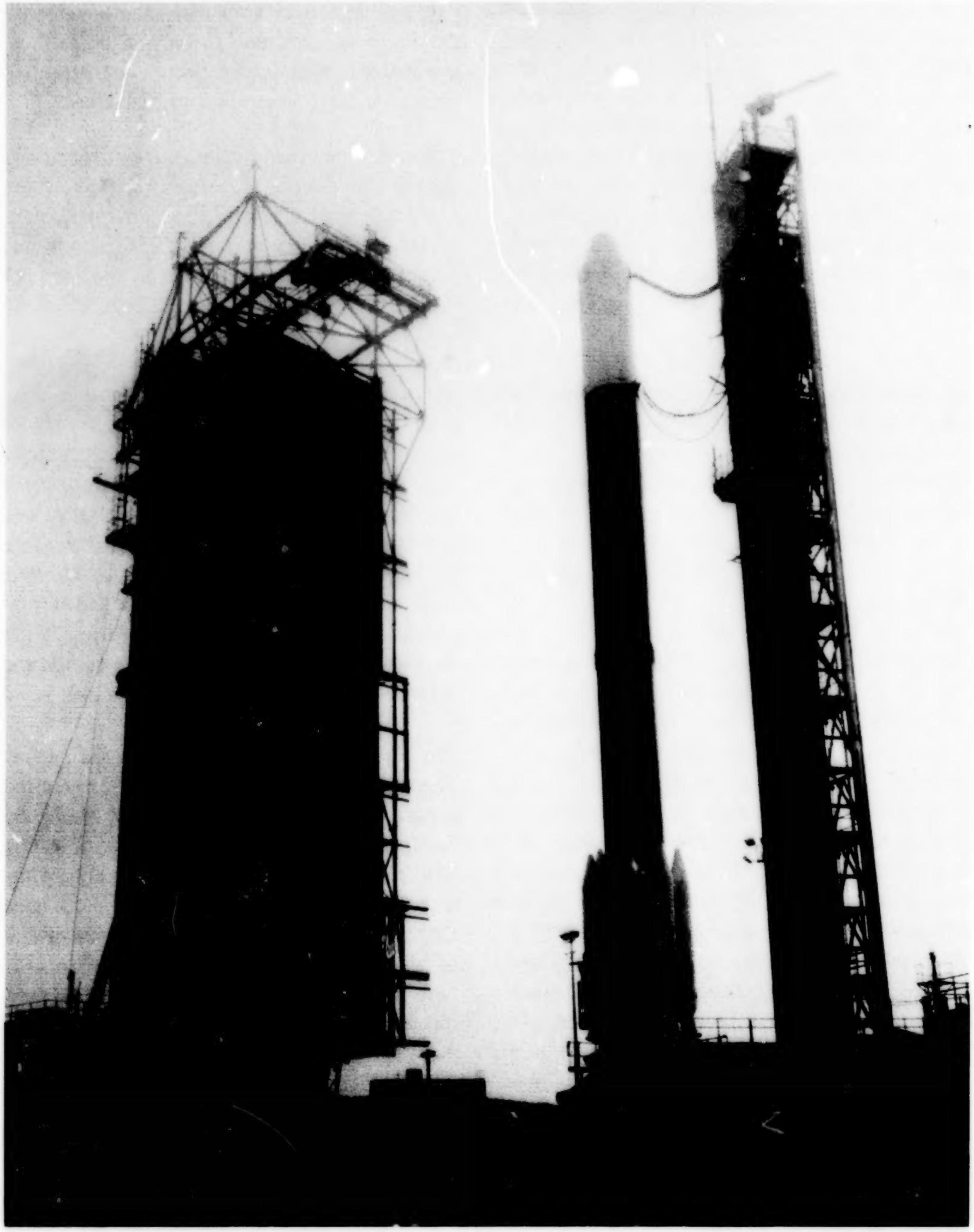

Figure 57. The impressive Thor/Delta launch vehicle with its strap-on boosters is readied on the launch platform at the Western Test Range. A short while later, it placed Atmosphere Explorer D into polar orbit.

spectrometer included a number of postlaunch procedures for refining and correcting the calibrations of the 24 monochromators of the instrument. Data from the monochromators were periodically tested to check their internal consistency. The data were also compared with data from the filter photometer carried by the same spacecraft, and as the mission progressed, data were occasionally cross-correlated with measurements made by high-altitude rockets and with ground-based observations of solar ultraviolet and solar activity.

By January 10, 1974, all spacecraft and instrument checks had been completed in orbit. All the spacecraft systems and instruments were operational, and the performance was nominal except that one of the programmers had experienced difficultly in handling its load. The orbital adjust system had lowered the perigee to 150 km in two stages.

After Atmosphere Explorer C had been in orbit about 1 month, the teams had explored all the various modes of operation and had decided which were best for gathering the most useful scientific data about the thermosphere. They were able to pinpoint the optimum experiment operational techniques for gathering the required data with very little time spent in nonproductive modes of data gathering. One of the big advantages of the rapid data turnaround for this mission, this ability to react quickly was extremely important because, as the orbit plane precessed, the perigee moved in latitude. No opportunity for repeat gathering of data would occur until the perigee came around to that latitude again, but then the season would be different. Consequently, it was extremely important to obtain the best data as quickly as possible in each mission.

The elliptical orbit phase began after the first month in orbit. During this period, operations consisted of normal scientific and engineering data acquisition in both real time and the recorded mode, altitude correction maneuvers, momentum wheel corrections, spin control maneuvers, and orbit adjust maneuvers.

Spacecraft data recording was scheduled mostly during the period of perigee passage of the spacecraft (figure 58). In general, the spacecraft-recorded telemetry operations consisted of one playback of the spacecraft tape recorder per orbit for coverage of about 30 percent of the orbit.

At approximately 2-week intervals, the spacecraft made low-perigee excursions to collect scientific data there. It remained in the low-perigee mode for about 24 hours before being returned to the normal perigee altitude. The first two or three perigee lowerings were accomplished in a series of about 10 steps over a period of several orbits while the capabilities of the spacecraft to operate properly low in the thermosphere were checked. Subsequently, the lowering took place in about four steps.

The first excursion took place March 6, 1974. The series of cautious maneuvers lowered the perigee to 139.8 km from 150 km above the Earth. Everything appeared to be operating well. Thirteen of the 14 instruments aboard the spacecraft performed as expected, and a large amount of data was acquired and transmitted to the operational control center. However, both filaments in the closed-source neutral mass spectrometer apparently failed, and the instrument could no longer make measurements. The cause, which was proved in the laboratory and corrected for all subsequent instruments, was determined to be faulty filament connections.

Atmosphere Explorer C blazed a trail into the lower thermosphere as its perigee was gradually dropped lower and lower. It was originally intended to attempt 120 km, but the investigators did not want to endanger the spacecraft.

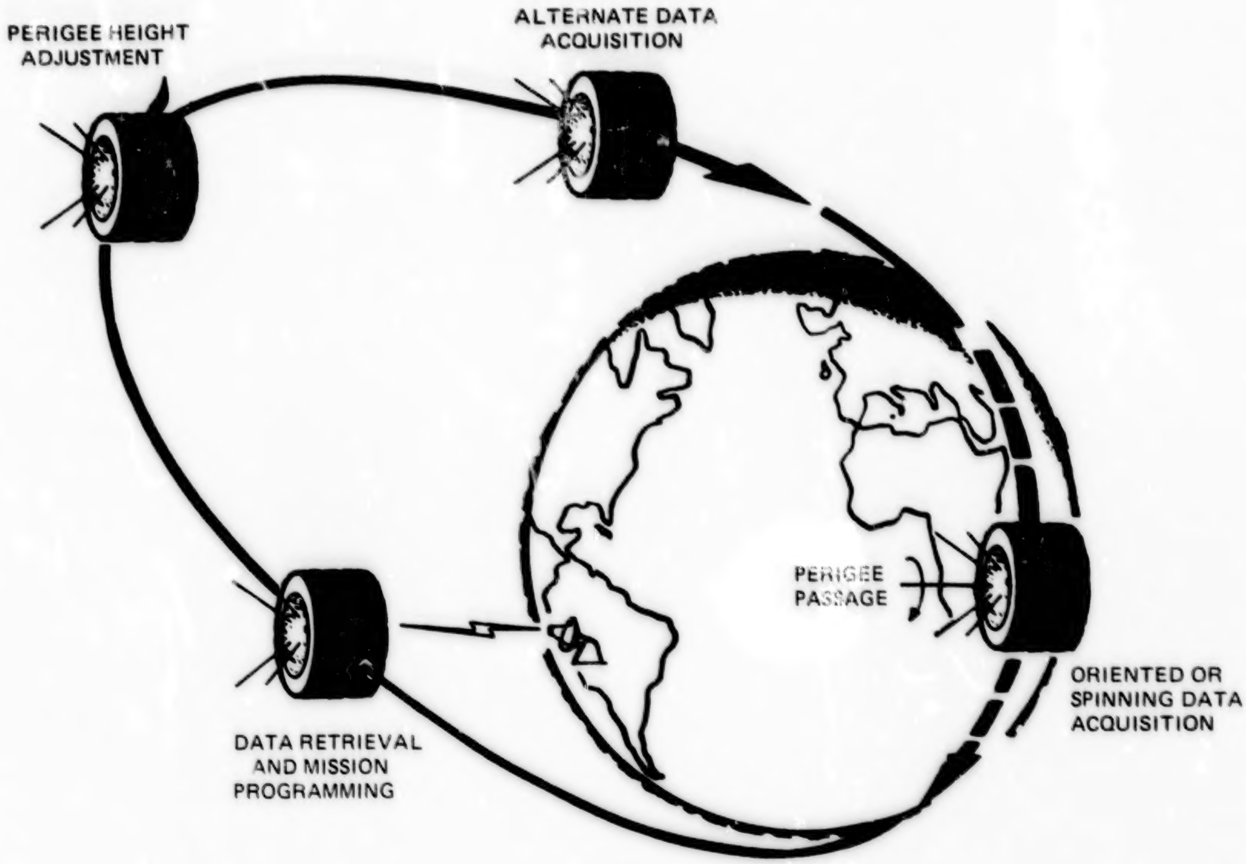

Figure 58. The orbit of the Atmosphere Explorers was an elongated ellipse. This artist's concept shows activities at several parts of the orbit.

The perigee was not lowered below 129 km because it was concluded that most of the instruments could not gather useful data below that altitude due to the high atmospheric density. The only major concern regarding instrument survival at the low altitudes involved the solar extreme ultraviolet spectrophotometer, and precautions were taken to prevent overheating of the solar pointing system at altitudes below 135 km. This subsystem was used to point the spectrophotometer entrance axis toward the Sun. In fact, heating of this platform due to passage through the atmosphere became the controlling factor of operations at low altitude.

The operation at low altitudes was exploratory because no one knew exactly what the instrument and spacecraft systems' temperature would be until the spacecraft had actually operated in these lower regions of the thermosphere.

An anticipated problem that did not prove as troublesome as expected was the trail of ionization produced by the spacecraft as it passed through the lower thermosphere. Several effects were actually measured: the radiation emitted by the passage and the ionization itself. The radiation appeared in the data from the

visual airglow photometer, and the charged-particle analyzers detected the electrons and the ions produced by the spacecraft's swift passage through the atmosphere. When these passages occurred at night, the ionization from the spacecraft was dominant over the low natural ionization.

August 4, 1974, was an important day in the Atmosphere Explorer program. The Atmosphere Explorer C had achieved its objectives of investigating the photochemical processes that accompany the absorption of solar radiation in the thermosphere and was judged officially successful. All 14 onboard scientific instruments had acquired useful data, and except for minor problems, the systems of the spacecraft itself had performed as expected. The propulsion system had been used on numerous occasions to adjust the perigee of the orbit and to restore the altitude of the apogee. Until this time, the lowest excursion into the lower thermosphere had been to an altitude of 129 km above the Earth's surface.

The circular orbit phase began approximately 1 year after launch and continued until the end of the mission. This circular orbit was achieved by allowing the apogee to decay to about 600 km, raising the perigee to the exact circular orbit altitude required, and then adjusting the apogee to that altitude.

Of the three spacecraft, Atmosphere Explorer D was expected to contribute the most global data. Because it orbited in a polar inclination, AE-D permitted the study of both polar regions, as well as the lower altitudes. Everything appeared to be going well, and the spacecraft was gathering important data. In February 1976, however, the signals from the spacecraft abruptly ended after a period of unusual measurements from the instruments.

It was determined that a serious problem had developed in the power system, and within a few orbits, all battery power was consumed and the spacecraft was lost. Because of the low perigee, the orbit decayed rapidly, and reentry occurred within a few weeks close to the South Pole on March 14, 1976, the day of the Goddard Memorial Dinner that is held annually in Washington. The possibility of sighting the final decay of the satellite was small because of the remote impact area, and it was not reported to have been seen.

It took some time to determine what had caused the loss of this spacecraft, but engineers finally unraveled the mystery. As explained previously, the Atmosphere Explorers had been developed from a Tiros spacecraft. Many engineering drawings for the Tiros had been used as a basis for the Atmosphere Explorers. During the process of drafting the new drawings from the old, washers had been omitted from three places under the anode of a diode of the satellite's power supply. This omission allowed a spade lug that carried a potential of 40 volts to eventually penetrate and char a Kapton insulator and lead to a dead short. Fortunately, this problem did not arise during the mission of AE-C.

Atmosphere Explorer D had lasted for 160 days in orbit. During this period, the perigee moved from the launch position at 10 degrees north latitude up over the north pole and then down the other side of the Earth to the south pole, where the power failure led to loss of the spacecraft. During the mission, a problem of nutation—a noding libratory motion of the spin axis of the spacecraft—prevented the instruments from acquiring temperature data and distorted measurements made by other instruments. Nevertheless, the necessary data corrections were made, and the spacecraft obtained much valuable data over a wide range of latitudes.

By contrast, Atmosphere Explorer C operated well throughout its mission, and it was placed into "orbital storage" in June 1975. At that time, it was operated only twice a week to supplement the data being obtained with AE-D and AE-E. When AE-D failed, AE-C was brought back into use on a continuing basis and then performed the polar equatorial science acquisition to the extent possible from its 67-degree inclination orbit. These data were not as extensive as those expected from AE-D because the orbit did not reach the poles.

Atmosphere Explorer E was also highly successful. By the end of 1977, it had completed over 10,000 orbits and was gathering data on only one orbit each day. Both AE-C and AE-E, therefore, had provided data far beyond their nominal missions and life expectancy. The wealth of data permitted many guest investigators to join the aeronomy team and make analyses beyond those contemplated in the original mission plan. Although the analysis of the data will continue for many years, the following chapter will present some of the early results.

DATA HANDLING

The handling of the data stream from the spacecraft was another major achievement of the Atmosphere Explorer program. The Atmosphere Explorer program's new approach to the handling, processing, analysis, and sharing of data was keyed to a central computer that was dedicated to the project. All data were processed by, and resided within, the computer system, and all investigators had access to it through remote terminals at the various universities and laboratories.

The major design goal for this satellite data processing facility was to provide for the rapid analysis of the scientific data and to provide a data pool that would be available to the scientists' terminals soon after its acquisition.

The Atmosphere Explorers gathered large amounts of data: several hours of operation of the instruments each day produced about 300 million bits of data. To facilitate the expeditious reduction and processing of this quantity of data, the data handling system required a dedicated computer. In addition, the system had to provide a variety of geophysical parameters needed by the investigators to analyze the processed data. The system also had to be able to store and display the new data about the thermosphere gathered by the satellites.

Thus, a major and significant function of the data system was to maintain a common pool of the scientific data in a form that was readily accessible to the investigators.

A natural progression of events must take place during a joint scientific endeavor that involves a number of investigators. It begins with the accumulation of the measurements made by the various instruments and culminates in the construction of theories that explain the observations.

Early in any mission, each investigator tends to concentrate on data from his instrument as he checks the quality of performance of his equipment and the validity of the measurements he is obtaining. When he is satisfied that the data are valid, he then focuses on keeping up with the processing of the large amount of data coming from the satellite. He devises techniques to interpret the data and to present it in a meaningful form.

Next, each investigator begins to correlate results with those of the other investigators. Following this phase, the investigators attempt to confirm existing theories or devise new ones to explain the empirical results recorded by the instruments.

To smooth this process for the Atmosphere Explorer program, the central computer made

possible three major components: a common data base, a data distribution system, and peripheral remote terminals. The central computer was a Sigma 9 with nine major programs. Five of these programs processed data to produce five file types in the data base. The other programs managed the mass storage devices, responded to requests from the remote terminals, and provided for file management and the generation of status reports.

The data files consisted of one for telemetry data such as engineering data about the spacecraft, one for geophysical information, one for data on the daily geomagnetic activity of the Sun, and one for data on the attitude and orbit of the spacecraft. Data gathered by the spacecraft and processed into geophysical terms were stored in unified abstract files that contained all the data on line since the beginning of the mission and maintained them for common access of the team members.

Therefore, a key element of the Atmosphere Explorer data handling system was the centralized on-line repository of data that were readily accessible to users through their remote terminals. The system worked well, but suffered from success. After several years of spacecraft operation, disk space was not sufficient for maintaining all of the data on line, even though the system had been provided with a full complement of disk packs. Most of the data were on disks, but the remainder were retained on 1600-bpi tape in a tape library (figure 59). Whenever a request for a file was received, the system checked its file catalog and determined whether or not the file was on disk. If not, the system automatically issued a message to the operator to mount the proper tape (as designated by the tape number) and promoted it to disk. None of the user application programs read or wrote directly to or from tape; they used disk files exclusively.

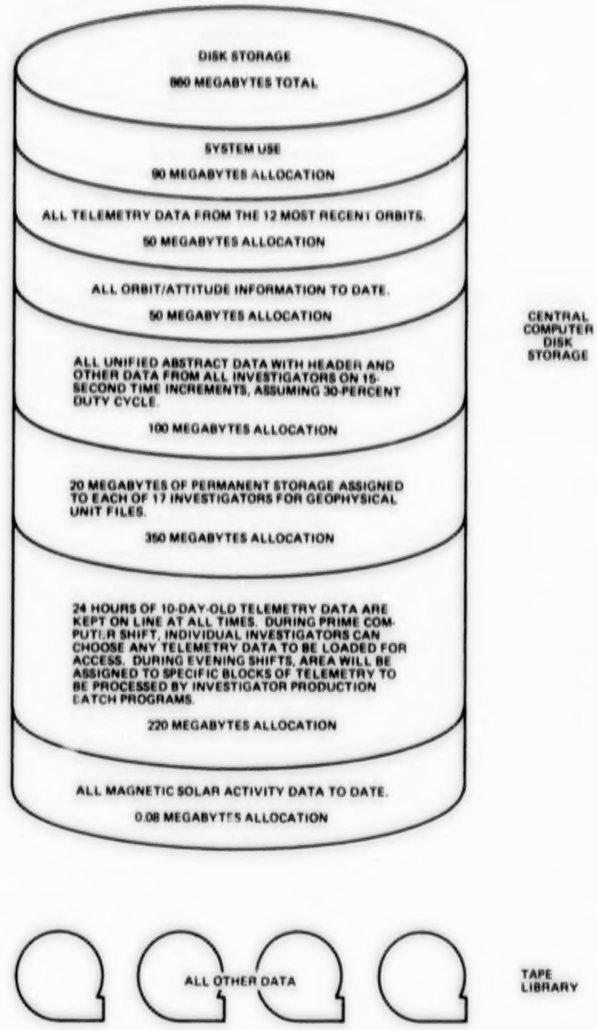

Figure 59. Data Base for Experimenters.

Most of the processing on the central computer involved the reduction and analysis of scientific data from scientific equipment on board the spacecraft. Each individual investigator was responsible for developing software programs for processing the data. To simplify this development and to ensure flexible data handling and sharing, standardized data-base files were established for the central computer and were made accessible through the Fortran language. Perhaps the most important of these files was the unified abstract file, noted previously. Organized by orbit number, the files contained

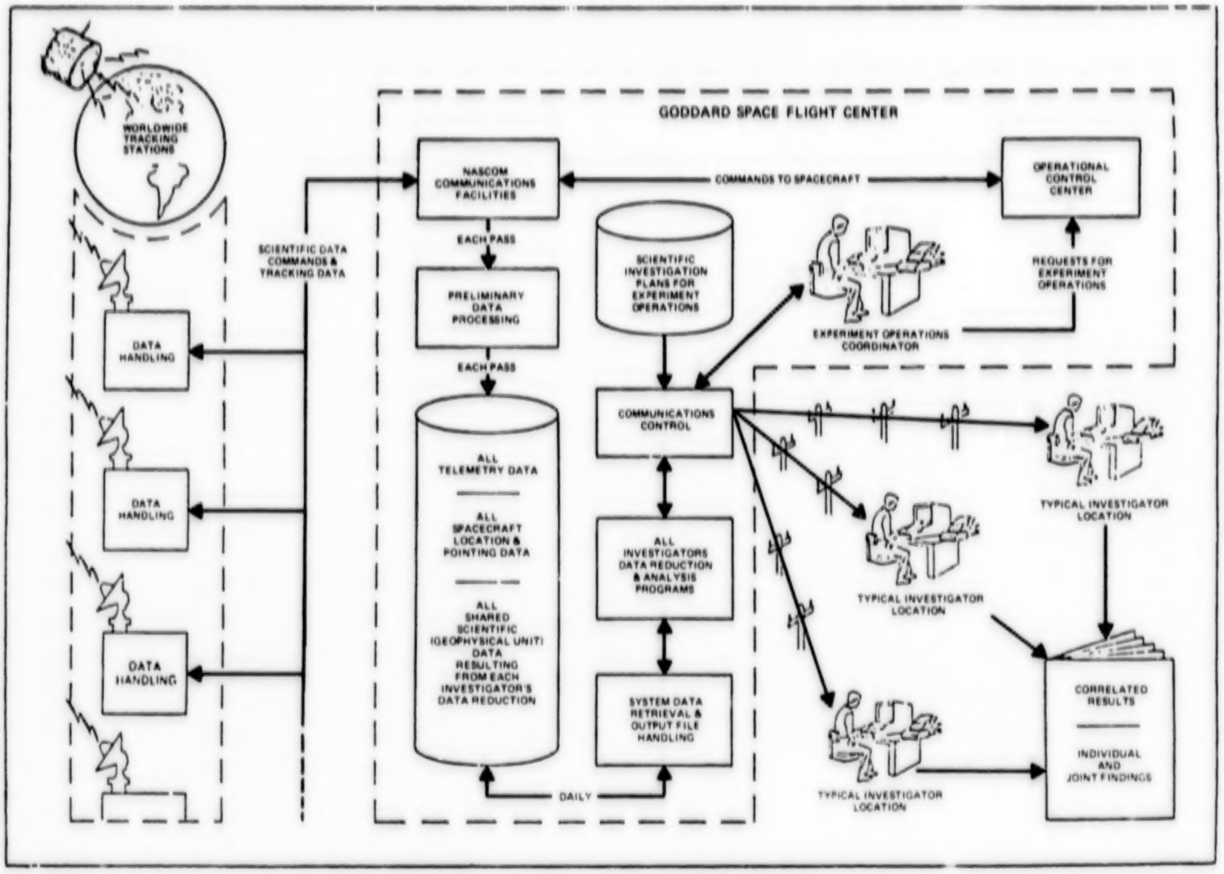

Figure 60. The data handling system used with the Atmosphere Explorers gave investigators, at their own facilities, the capability of rapidly gaining access to both their data and that of other investigators.

single header records of general information and point-by-point records of the final data spaced 15 seconds apart.

Reserved space for all data and associated maintenance was set at 300 million bytes. Each investigator could write in the area reserved for data from his instrument and could read from any area of the files (namely, from all the data on line since the beginning of the mission).

Figure 60 shows the data handling system. The spacecraft were tracked by stations of the Deep Space Network (DSN) through transponders carried by the spacecraft. A 137-MHz beacon operated continuously to provide minitrack data and to allow elements of the DSN to acquire the satellites easily. Using this system, after each orbital adjustment, the new orbit could be verified within 15 minutes.

All spacecraft data and selected science data were transmitted to the Operations Control Center as received on the ground, and other data were forwarded quickly afterwards to permit processing within 2 hours after the satellite passed over each ground station.

At the Operations Control Center, a Sigma 5 computer monitored the verification of all commands sent to the spacecraft, as well as the status of the science instruments, and served as

an input processor for the central data processor. The Sigma 5 also served as a backup to the main computer of the system and to the central computer for another satellite program.

Providing short turnaround times of one to several days on the analysis of selected aeronomy problems permitted adaptive mission planning while a spacecraft was in approximately the same relative location (i.e., same position of perigee). For example, if the aeronomy team noted that, during a low-perigee excursion at a particular latitude in the Northern Hemisphere, a highly disturbed condition of the thermosphere was apparent, they might have wanted to study it further. The fast turnaround time of the central processor enabled them to be aware of the disturbance and adaptively replan the mission in time to observe the disturbance (e.g., they might have wanted to continue observations for another 3 days at a perigee of 140 km).

The computer system used for supporting data processing for the Atmosphere Explorer missions was a combination of a Xerox Data Systems Sigma 5, Sigma 9, Sigma 3, and remote terminals (table 5). The Sigma 5 was connected to the remote telemetry acquisition sites through NASA's communications network. This computer served as an input processor to the Sigma 9, which in turn was connected to the investigators through the Sigma 3 communications processor and remote terminals.

The Sigma 5 possessed sufficient direct access storage to buffer data input simultaneously from three remote telemetry acquisition sites, to collect, time correct, and verify the data, and to rapidly transmit the resulting data to the Sigma 9 central processor.

At the central computer the latest data were stored in a file that could be accessed directly for data inspection. A library of all data was recorded on tape.

Table 5
Central Data System Hardware

Equipment	Peripherals and Other Equipment	No.
Central Computer (XDS Sigma 9*)	Seven tape units	7333
	Three tape units	7322
	Two line printers	7441
	Two keyboard teletypewriters	7021
	Two keyboard teletypewriters	7015
	One card reader	7140
	One card punch	7160
	Two rapid-access memories	7212
	Fourteen disk packs	
Input Processor (XDS Sigma 5)	Two line printers	7441
	One line printer	7440
	Six magnetic tape units	7332
	One rapid-access memory	7204
	One disk storage unit	7242B
	One keyboard printer	7012
	One card punch	7160
	One card reader	7122
	One paper tape station	7060
	Six keyboard CRT display units	
Other Equipment	Sanders 810 programmable remote terminals	
	Calcomp 763 plotter	
	Stromberg-Datagraphix 4060 microfilm data recorder/plotter	
	Tektronix 4002A terminal	
	Brush Mark 200 strip-chart recorder	

*A Sigma 3 computer was connected to the Sigma 9 to serve as a controller of communications with the remote terminals.

Each investigator, having a remote terminal connected to the computer by dedicated telephone lines, could reduce and analyze these

Table 6
Central Computer Programs

Name	Inputs	Outputs
Telemetry	Telemetry data	Updates to data base
	Access requests	Backup tapes Telemetry data retrieved Error and status flags
Orbit/attitude	Spacecraft orbit data	Updates to files
	Spacecraft attitude data	Backup tapes Data retrieved Error and status flags
Magnetic solar activity	Solar activity	Updates to files
	Access requests	Data retrieved Error and status flags
Mass storage manager	Data to be transferred	Directory searches Directory updates Data retrieved
Data base inquiry	Access requests	Data retrieved
Utility	File maintenance commands	Data-base directories
Unified abstract	Analysis results	Data retrieved
File	Access requests	
Accounting report	Status requests	Reports

data through the software and techniques he had developed at his terminal. He could submit both interactive and batch programs and include at his site CRT displays, high-speed printers, and card readers. All of the data base, as well as the facilities of the central computer, were made available to the investigator through these terminals. Such facilities included common orbit/attitude interpolation, scientific and numerical analysis routines, and the normal service of an interactive/batch time-sharing operating system (table 6).

The computer system included a data handling facility for handling the user files and requests for data. It automatically retrieved telemetry data from the tape library and placed it into files that could be accessed directly. It responded to user's programs in the Fortran computer language using standard interfaces. In addition to automatically retrieving telemetry data, this facility retrieved orbit, spacecraft attitude, and magnetic solar data from direct-access files and wrote and retrieved data from geophysical files created by the data reduction programs of the investigators. The combination of telemetry, orbit/attitude/magnetic solar activity, geophysical unit, and unified abstract files formed the major data base of the system.

The aeronomy team developed requirements for a correlative measurement effort in support of the Atmosphere Explorer mission. The measurements were made by satellite and

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Figure 61. The Atmosphere Explorer mission involved many people working in teams and sharing data for many investigations.

rocket-borne instruments and by ground-based instruments. For example, Atmosphere Explorer C data were correlated with data from three other satellites: ISIS, Aeros-B,* and San Marco 4. The ISIS was in orbit and functioning well when Atmosphere Explorer C was launched, and correlative measurements were successfully made. Aeros-B and San Marco 4 offered international cooperative programs for only a short while. Aeros-B reentered in the fall of 1975, and San Marco in the spring of 1976. The low inclination of San Marco's orbit offered opportunities for making neutral particle measurements that could not be made with Atmosphere Explorer C in its high-inclination orbit.

Data gathered by San Marco 4 in the equatorial zone and Atmosphere Explorer C in the auroral zone provided a picture of the effects of magnetic storms on the thermosphere and the differences in the response of the thermosphere to energy coming from the Sun into the atmosphere at the poles and at the Equator.

In another example, during a 4-day period beginning June 30, 1974, NASA and the Air Force Cambridge Research Laboratory, in participation with more than 100 U.S. and foreign experimenters, launched 54 sounding rockets from Wallops Flight Center as part of the Atmospheric Layering and Density Distribution of Ions and Neutrals (Project Aladdin 1974) program. In addition to these rockets, which were launched during the 24 hours beginning at 1:00 p.m. Eastern Daylight Time on June 29, 1974, a chemical experiment was launched on board a Nike-Iroquois on June 28, and four meteorological rockets were launched on July 1. Chemical releases made yellow to yellowish-green vapor trails over the East Coast for tracing high-altitude winds.

The objective was to study dynamic and structural conditions of the lower thermosphere by means of small meteorological rockets, chemical releases, falling spheres, and spectrometers. Winds and temperatures were measured and patterns and dynamics were revealed. The data received were compared with those being acquired by Atmosphere Explorer C.

Another example was the use of an Aerobee 200 launched March 20, 1974, from Fort Churchill, Canada, in conjunction with good aurora and an overpass of Atmosphere Explorer C. In addition, a Nike-Tomahawk was launched from Wallops Island on December 6, 1974, to measure the distribution of nitric oxide molecules between 100 and 300 km in conjunction with an overpass of Atmospheric Explorer C.

Ground-based observations also supported the Atmosphere Explorers. Incoherent scatter of radio waves was measured from the Jicamarca Radar Observatory, and airglow measurements were made by the University of Alaska.

An important feature of the Atmosphere Explorer mission was the continuing series of bimonthly meetings of the science teams to review results and future operations (figure 61). Major meetings in the form of symposia discussed the science results in depth. The first of these took place in 1976 and the second in 1978, and detailed proceedings were published. In addition, the various investigators published hundreds of technical reports and papers during the mission (Appendix C).

Because of the great complexity of the thermosphere, correlative research became extremely important in making full use of the enormous quantities of data gathered by the Atmosphere Explorers. Three theorists of the original aeronomy team continued through the program, and many guest investigators participated later. The following chapter summarizes some of the more important results from the program.

*German Aeronomy Satellite.

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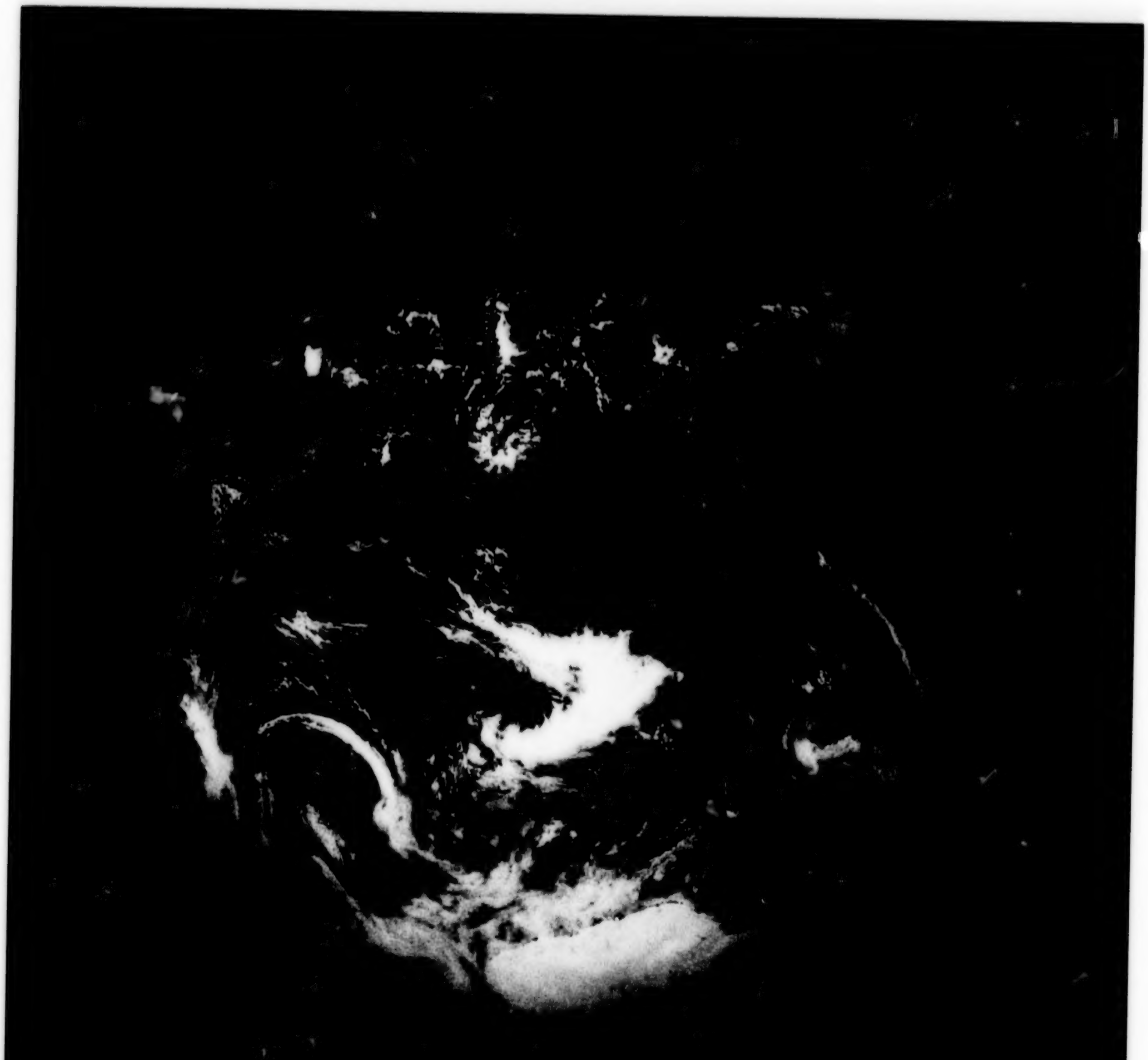

6

A NEW LOOK AT THE THERMOSPHERE

The Atmosphere Explorers gathered a substantial amount of new data during their missions. Not only did the initial experimenters use these data to answer the questions set for their scientific tasks at the beginning of the program, but many guest experimenters also used the data for correlative studies. In addition, new investigations were begun during the missions on the basis of results obtained earlier in each mission. In this area, the adaptability of the satellites and their instrumentation paid great scientific dividends.

Although the analysis of scientific data from the Atmosphere Explorers will ultimately take many years, many new conclusions have been drawn about the thermosphere. The first scientific objective of the missions was to gain information about the energetic processes within the thermosphere.

ENERGETICS OF THE THERMOSPHERE

Although measurement of the portion of the extreme ultraviolet spectrum that is responsible for photodissociation of molecular oxygen was completed with the Atmosphere Explorer C, the region of the spectrum below 1027 A was not covered in the detail anticipated because of problems with the extreme ultraviolet spectrometer. However, the instrument aboard AE-E functioned well throughout the mission. Good data were also received from AE-D until it failed as described in the previous chapter.

Data from the absorption of solar extreme ultraviolet radiation were successfully gathered. Absorption analyses of thermospheric structure were obtained not only for the regions of the orbit sections near perigee but also for sunrise and sunset regions of the atmosphere. The latter data added information on the structure of the atmosphere that extends well below the perigee of the satellites. This observational technique also provided atmospheric profiles that are more truly "vertical" than could be obtained by *in-situ* sampling along the orbit of the satellite.

The photoelectron spectrometer measured low-energy electron fluxes. The two sources of error in such an instrument are stray electric and stray magnetic fields. Even though none of the Atmosphere Explorers could be classed as magnetically clean, the instrument worked well down to 1 electron volt. Modifications to sensor 1 on AE-E before launch so that it would look along the spin axis paid dividends in avoiding magnetic field shielding while providing the best data from the standpoint of freedom from errors due to electric fields.

Many hundreds of spectra of the low-energy electron fluxes were obtained during the missions. Those observed in the daytime thermosphere were in good agreement with theoretical predictions. Peaks in the flux observed at low altitudes were readily identified as being the result of strong photoionization by the solar

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radiation at 304 A. Smearing of the spectral lines observed at higher altitudes was attributed to electron-ion collisions suffered in transit from the production region below. The instrument gathered important information in the polar regions, including the first-time mapping of the low-energy electron distribution in the polar cusps at low altitude. It also provided information about the precipitation of very low-energy electrons in the auroral zone.

Suprathermal electrons produced by photoionization of the neutral atmosphere have a unique energy spectrum. They were observed to be precipitating into the nighttime ionosphere. Because they could not have been formed locally in the absence of solar ultraviolet radiation, this precipitation indicated that such electrons can be transported from the sunlit hemisphere to the one in darkness. Differences in magnitude between the photoelectron fluxes on the dayside measured by Atmosphere Explorer E and the calculated values were partially explained by the transport of these so-called conjugate photoelectron fluxes. Measured by the satellite, such fluxes were quite large at 250 km.

The three Atmosphere Explorer spacecraft observed some anomalous events at the middle and low latitudes. The first, on orbit 365 of AE-E, showed a monoenergetic flux of electrons superposed on a normal daytime spectrum that shifted in energy from about 14 to about 2 electron volts. This type of event was seen only by AE-E, and it occurred in both daylight and darkness. Because it occurred only when the spacecraft was oriented in a certain way to the Earth's magnetic field, the event was assumed to be caused by electrons originating in the wake of the whip antenna of the spacecraft. Another monoenergetic peak about 2 eV wide was also observed at certain orientations of the spacecraft. This peak was also attributed to the spacecraft.

The Atmosphere Explorers were expected to provide information about the thermosphere, but they also provided much new information about the magnetosphere. Since the magnetosphere has such important influences on the ionosphere, the new information was extremely valuable for increasing our understanding of the lower regions as well. For example, it was discovered that, during extremely quiet magnetic conditions, significant processes are taking place that enable particles from the magnetosphere to enter the polar regions of the ionosphere.

The region near the magnetospheric cusps proved to be one of intense particle precipitation in which the particle flux reaches significant levels. Furthermore, the particles appear to be there on a permanent basis so that they must result in heating and chemical changes in the atmosphere. Measurements of high-energy electrons suggest that the last closed-field lines are located in this region of precipitation. Because the cusp region is probably located above the last closed-field line, the particles may originate in the solar wind. Some work was directed toward identifying the positive currents directed into the ionosphere to determine if protons are also precipitating downward, as opposed to low-energy electrons moving upward. The data so far appeared to indicate that there are not sufficient protons to form the currents known to exist in the region.

As the distribution function of auroral particles was measured with increasing completeness, it became evident that a class of electron precipitation, called inverted-V events, is relatively common. First observed on the ISIS and Injun spacecraft, this class of events was investigated by Atmosphere Explorer D, which carried one of the most comprehensive auroral particle instruments. It was found that the events occur at all local times, but in the dayside hemisphere,

they occur at higher altitudes than in the night-side hemisphere. They span the shortest latitude range in the hours before dawn. Because the perigee altitude of Atmosphere Explorer was below the region in which many of the particles in the events interact with the atmosphere, the investigators were concerned as to whether a decrease in occurrence around noon was due to perigee passage through the region. They decided, however, that the decrease in the number of particles was not an altitude-induced effect.

Results were interpreted as meaning that the precipitating electrons are heated in an accelerating region above. This heating arises from the same plasma instabilities that create the accelerating electric field parallel to the Earth's magnetic field. One of the remarkable discoveries was of fluctuating fluxes in some of the inverted-V events. A speculation is that they are derived from plasma instabilities that produce an anomalous resistivity associated with parallel electric fields in the region that are believed to be responsible for accelerating the electrons. Studies of the characteristics of auroral electron acceleration regions on the nightside of Earth revealed that energetic electrons could have energy spectra consistent with their having been accelerated through several kilovolts of electrical potential.

Using the retarding potential analyzer drift-meter data, investigators sought information on the processes by which solar wind plasmas and electric fields penetrate the magnetosphere, how the plasmas are then transported and energized within the magnetosphere, and how the momentum and energy carried by these plasmas is then deposited in the thermosphere. Figure 62 shows the dayside high-latitude ion convection pattern derived from AE-C data. The shaded region is the region of proton precipitation in the polar cusp. The view is looking down on the northern polar cap ionosphere. The constricted flow region (shaded area) near 12:00 local time is believed to be connected to a region of the magnetosphere through which magnetospheric plasmas flow onto field lines connected to the solar wind and where solar wind plasmas are injected into the magnetospheric cusps on the dayside of the Earth. By comparing a number of energy-latitude patterns of electron and proton data with the simultaneous ion-drift measurements from the drift-meter, the investigators were able to estimate the distance to the region where the cusp protons are injected.

A consistent feature of the antisunward flow in the ionosphere is its expansive nature. The convective trajectories that lie close to the polar

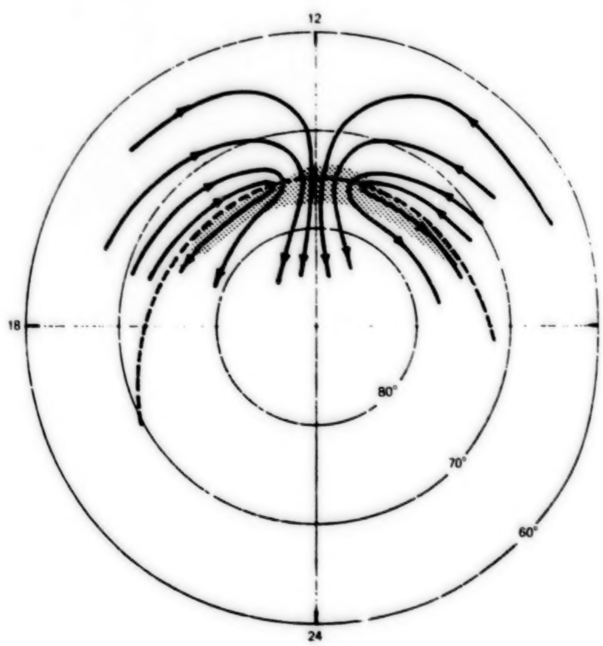

Figure 62. Schematic view of the dayside high-latitude convection pattern derived from ion velocity data from Atmosphere Explorer C. The dashed line represents the boundary of the polar cap, and the shaded area is the region where protons precipitate through the polar cusp.

cap boundary tend to follow paths that are parallel to the boundary, indicating that substantial portions of the dayside polar cap boundary are nearly electric equipotentials.

The rotational reversals appear in a restricted region of local time near noon, a region that has been termed "the throat." The ionospheric plasma that is involved in the high-latitude convection pattern flows through this throat into the polar cap, where expansive flow then occurs. The throat may be a signature of the interaction between the Earth's magnetic field and the interplanetary magnetic field.

At lower latitudes, the more horizontal nature of the magnetic field allows the neutral winds of the F-region to drive the charged plasma along the field tubes, resulting in drastic changes to the distribution and temperature of the plasma. Solar minimum conditions during the Atmosphere Explorer D mission allowed both ionized atomic oxygen and ionized atomic hydrogen to be detected, and for the first time, a reliable measurement of the bulk plasma velocity vector was made.

The most dramatic effects of plasma transport between hemispheres in the equatorial ionosphere were seen above 600 km, where high ion-drift velocities of about 500 meters per second were measured (figure 63). The transport of plasma is caused by neutral winds in the F-region blowing across the Equator from summer to winter. The resulting motion of the ions is then up the field tubes in the summer hemisphere and down them in the winter hemisphere.

The motion of plasma up the field lines to lower number densities in the summer would be expected to cool the ions adiabatically (i.e., without exchanging heat with their surroundings), whereas the motion down the field tubes in winter would have the reverse effect

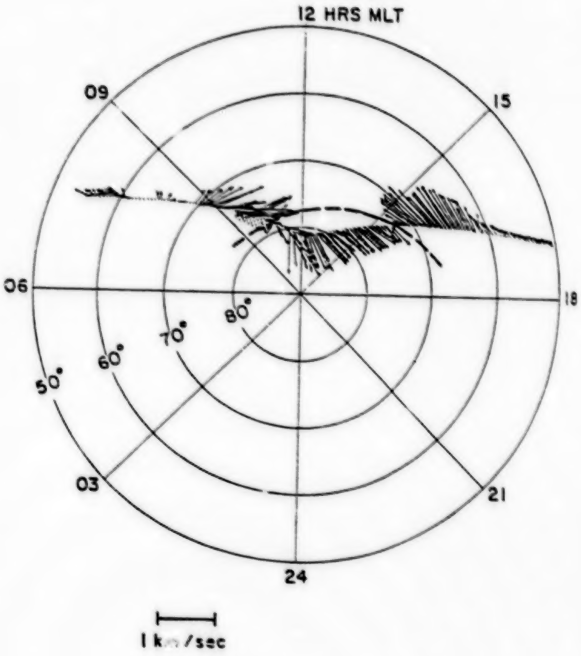

Figure 63. Ion-drift velocities measured from Atmosphere Explorer C in a passage close to the south polar regions. A rotation of the flow direction without much change in velocity occurs close to the shaded area.

of heating the ions. Ion temperatures measured by the Atmosphere Explorers were lower than those expected of the exosphere on the summer side of the magnetic dip equator, suggesting that this plasma motion can produce supercooling in the summer hemisphere.

CHEMISTRY OF THE THERMOSPHERE

Variations in atomic hydrogen and molecular oxygen within the thermosphere were inferred from the ion chemistry. The neutral atomic hydrogen is difficult to measure directly. However, by using measurements of the ratio of ionized hydrogen to ionized oxygen (made with the ion spectrometer) and the neutral oxygen measurements (made with the open-source neutral spectrometer), the amount of neutral hydrogen was calculated for the region below 250 km, where chemical equilibrium holds.

Results demonstrate that the concentration of hydrogen in the thermosphere is higher at all latitudes during the night than during the day. A seasonal variation also occurs in which the concentration in the winter hemisphere exceeds that in the summer hemisphere. This confirmed the presence of the winter hydrogen "bulge" similar to the helium bulge discovered earlier. The same technique was used to determine what happens to hydrogen during magnetic storms. The concentration of hydrogen falls during the storm, whereas the gas temperature rises.

Molecular oxygen is also a difficult gas to measure directly in the thermosphere. The concentrations of this gas were calculated by using an ion chemistry approach. Although they are not straightforward because they contrast somewhat with earlier interpretations of data from an Orbiting Geophysical Observatory, the results indicate that there is a bulge of molecular oxygen in the summer thermosphere as a result of photodissociation of molecular oxygen at periods of low solar activity.

Above the magnetic equator at night, the primary processes responsible for the production and loss of the molecular ions of nitric oxide and oxygen were identified as follows:

NO^+ Production $O^+ + N_2 \rightarrow NO^+ + N$ (outside O^+ trough)

$O_2^+ + NO \rightarrow NO^+ + O_2$ (inside O^+ trough)

Loss $NO^+ + e \rightarrow N + O$

O_2^+ Production $O^+ + O_2 \rightarrow O_2^+ + O$

Loss $O_2^+ + e \rightarrow O + O$ (outside O^+ trough)

$O_2^+ + NO \rightarrow NO^+ + O_2$ (inside O^+ trough)

However, comparison of theory with ion spectrometer measurements indicates that the equilibrium chemical theory does not adequately describe what is happening at the underside of the F-region, where there is a steep gradient in the density of ionized atomic oxygen. Dynamic effects appear to be at work, and some of the observed enhancement of ionized nitric oxide could result from plasma being raised from lower altitudes. In fact, driftmeter measurements show evidence of an upward flow of plasma in this region. In addition, the ionized atoms of iron appear to peak in the same region of the nighttime F-region. Moreover, this enhanced concentration of iron ions was observed at midlatitudes. Dynamic processes appear to be responsible for raising the iron into the F-region from its source level near 100 km, where most meteors disintegrate.

The ultraviolet nitric oxide spectrometer produced many interesting results, showing that nitric oxide at about 105 km varies with latitude, longitude, and level of solar activity, with a minimum near the Equator and a maximum at high latitudes. This suggests a connection with magnetic activity, and the Atmosphere Explorer measurements confirmed that the concentration increases with increased magnetic activity. Observations over a number of consecutive orbits showed a regular, almost sinusoidal, variation of nitric oxide concentration with longitude. This variation is of sizable amplitude and has a maximum in the western hemisphere. Global plots of the concentrations revealed regions of maximum and minimum concentrations of nitric oxide at 105-km altitude that are asymmetric about the geographic and geomagnetic poles but symmetric about the dip pole.

During a magnetic storm in September 1974, the neutral densities and temperatures were greatly perturbed, and nitric oxide in the F-region increased by almost ten times its normal

concentration. This increase was almost directly related to the increase in temperature and in the amount of molecular oxygen there. In the E-region, a magnetic storm caused somewhat different behavior of nitric oxide–one that was more difficult to interpret. As the storm progressed, nitric oxide concentrated at the Equator. This concentration could have been due to the downward diffusion of nitric oxide concentrations at higher altitudes.

Another series of measurements made during magnetic activity was aimed at confirming the theory of latitudinal gradients in nitric oxide concentrations. It was confirmed that an auroral source of nitric oxide must be transported toward the Equator even at times of only moderate magnetic disturbances.

The analysis showed that, in general, E- and F-region nitric oxide is a function of both latitude and magnetic activity. E-region nitric oxide also displays a longitudinal asymmetry with respect to both geographic and geomagnetic poles. The theoretical models of nitric oxide concentrations, however, needed further work to make them agree with the observations. In the F-region, the existing models were fairly satisfactory, but there were major differences in the E-region. In particular, the then-existing theory failed to predict the observed latitudinal gradient at 105 km. In general, it was found that nitric oxide is a very sensitive indicator of conditions in the thermosphere.

Atmosphere Explorer also played a useful role in studying the photochemistry of several newly discovered metastable ions and enabled many of the reaction rates to be determined quantitatively for the first time. The satellites showed that metastable ions play an important role in the photochemistry of several major ions. (See figure 64.)

The Atmosphere Explorer data base was also used to solve some of the problems in aeronomy that had been outstanding for a long time. The comprehensive nature of the data base and the remarkable consistency achieved when the various parameters were used together was demonstrated many times. The theoretical work involved using data from several hundred orbits to investigate the dissociative recombination of ionized nitric oxide. An analysis showed that, among other things, atomic nitrogen affects the photochemistry of ionized molecular oxygen. In addition, data from a few orbits were used to study doubly charged atomic oxygen ions that were formerly believed to originate from photodissociation of atomic oxygen ions by ultraviolet radiation at 351 A. This process could not account for all the doubly charged ions observed by the Atmosphere Explorers. A search for another source of doubly ionized oxygen led to the identification of a new process–direct double photoionization of oxygen at a wavelength of less than 254 A–as controlling the daytime F-region abundance. The Atmosphere Explorer C measurements provided estimates for the rate of this basic atomic process.

Other similar studies studied the theory behind the diurnal variation of ions in the F1-region. Ion composition measurements were applied to interpreting data from incoherent backscatter radar to avoid ambiguities in determining the ion composition and the electron and ion temperatures. The new theory derived from Atmosphere Explorer results was used to calculate the temperature near the 200-km level. A day of backscatter observations from the big radio telescope of the National Astronomy and Ionosphere Center at Arecibo, Puerto Rico, were processed according to the old and new theories. The results showed higher temperatures of electrons and ions, which may account for a long-standing discrepancy between

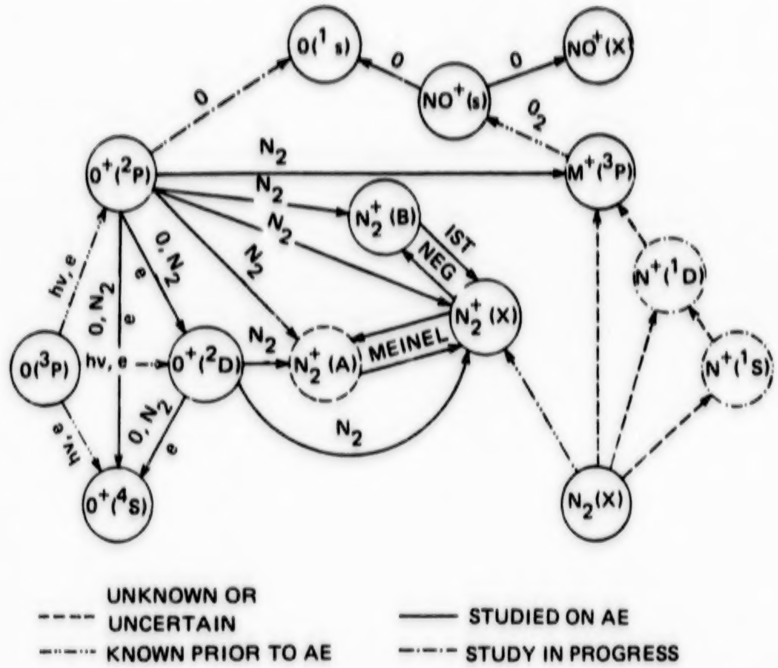

Figure 64. Atmosphere Explorer measurements were used to study the process involving metastable ions in the thermosphere.

ground-based calculations of temperature and those determined by *in situ* Langmuir probe measurements. This discrepancy now appears to have been resolved.

A unique set of measurements was obtained on February 14, 1974, when Atmosphere Explorer C passed directly over the incoherent scatter radar station at Millstone Hill (near Boston). Simultaneous data were obtained from both the radar and the satellite's instruments. The satellite measurements of electron density were in good agreement with the model calculations and the electron density derived from the radar observations. The calculated and observed ion compositions and densities were also in good agreement. However, some small discrepancies still existed between the satellite measurements of ion and neutral gas temperatures and those calculated from the radar observations. The next orbit showed better agreement, perhaps because of a reduced amount of atomic hydrogen ions on the second pass.

PHOTOCHEMISTRY, PHOTOELECTRONS, HEATING, AND AIRGLOW

The general problem tackled by the Atmosphere Explorers was to determine how the energy of solar ultraviolet radiation becomes distributed between 140 and 400 km among photoelectrons, photochemistry, airglow, and heating particles. One of the important results was the verification of dissociative recombination rates for molecular oxygen and nitrogen ions.

Ionosphere electron energy balance was studied using temperature and density data, and the equality of local and nonlocal electron heating rates was established below altitudes of 350 km. In the local regime, three independent heating rate calculations proved to be nearly identical. Cooling rates taken from theory, however, were consistently larger than the heating rates. A cooling rate was derived, but nevertheless, analysis of heating and cooling rates computed from a large number of satellite orbits showed

lack of equality. The trends of excessive cooling near perigee and excessive heating at high altitudes and at high to midlatitudes were identified. Energy balance was satisfied by the heat conduction equation for mid and high latitude regions. As a result, some progress was made in furthering our understanding of electron energy balance in the thermosphere. It was found that energy balance required three-dimensional calculations at low latitudes and that heat conduction in the thermosphere is important at all altitudes above 160 km.

Although the static state of the thermosphere and of its photochemistry was more thoroughly understood as a result of the Atmosphere Explorer results, thereby achieving the first goal of the missions, much work still needed to be done to understand the dynamic processes such as polar convection, the aurora, the equatorial convective and wind-driven processes. These dynamic processes were to be investigated by the Dynamics Explorer program of NASA that followed the Atmosphere Explorers.

A two-dimensional inversion technique was applied to airglow observations of the resonant emission from Mg^+. This technique produced maps of concentrations of this ion as a function of altitude and position along the track of the satellite. How the ion density varies as a function of local time, latitude, and longitude was observed. The two-dimensional inversion technique was also used to study the morphology of the nighttime 6300 A emission in the tropics. The resultant morphology pictures (figure 65) were interpreted in terms of drifts ($E \times B$) in the ionization, a transequatorial wind, and the semidiurnal tides that cause the tropical pressure maximum near midnight.

Observations of the emission from the airglow at 5200 A by Atmosphere Explorer filled a gap in knowledge. This emission had not yet been observed by rocket-borne instruments because of background radiation from the galaxy. It originates from transitions between energy levels of atomic nitrogen. The Atmosphere Explorer observations indicated a rate coefficient for the process that was much smaller than that determined by laboratory experiments, and that the reactions must be working at high efficiency in the thermosphere.

The green line (5577 A) of oxygen was also observed, with interesting results. Although rocket-borne instruments had made many observations of this dayglow emission, investigators had never had simultaneous composition data to use in conjunction with the airglow measurements. The Atmosphere Explorer provided such composition data in the F-region where the emission originates. An additional reaction was identified as accounting for the magnitude of the observed emission at altitudes below 220 km. Past studies indicated that the sources were the electron impact excitation of atomic oxygen and the dissociative recombination of molecular oxygen ions. The additional source was identified as a reaction between nitrogen atoms and ionized oxygen molecules that result in ionized nitric oxide and ionized atomic oxygen.

Atmosphere Explorer C and a sounding rocket were also used to investigate the nightglow emission at 5577 A. The source of ionized atomic oxygen for the emission appears to be the combination of three atoms of oxygen, which produces molecular oxygen and an atomic oxygen ion (Chapman mechanism) rather than the combination of a molecule of oxygen with an oxygen atom (Barth mechanism).

Transitions of atomic oxygen at 7319 and 7330 A were examined in the dayglow for several orbits of two Atmosphere Explorers. The production of the ions in the daytime is

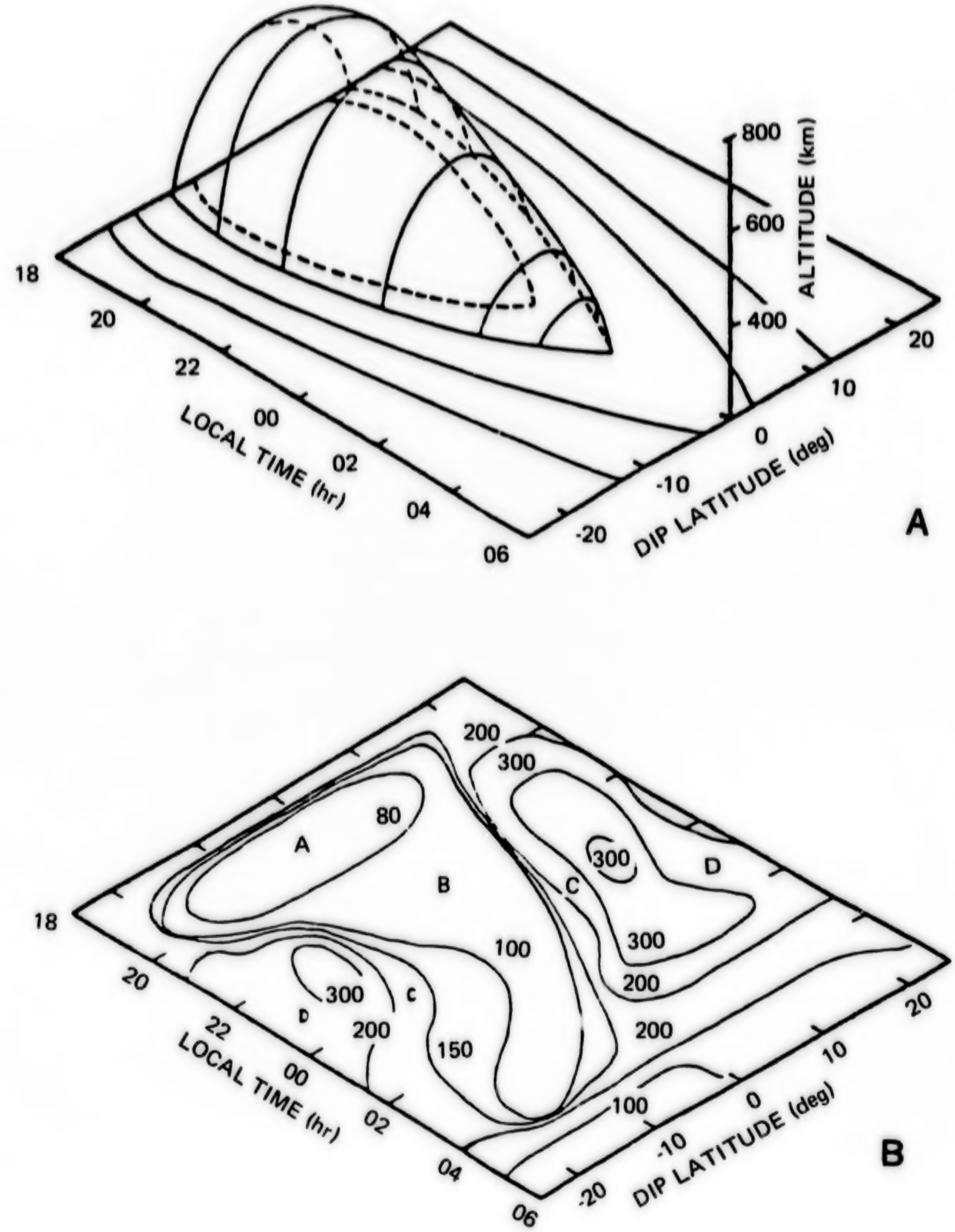

Figure 65. A two-dimensional inversion technique was used to study the morphology of the nighttime 6300 A emission in the tropics. (A) Schematic illustration of the intersection of magnetic flux tubes and a plane at 20 km (a three-dimensional diagram in local time, altitude, and dip latitude). In this representation, the field tubes follow the behavior of E X B drifts measured in Jicamarca. The diagram shows how the plasma first rises and later moves downward to regions of enhanced 02+ recombination. (B) Average global map of the 6300 A emission. The contours shown have units of Rayleighs. The morphology observed here is similar to what one would expect from considering the effect of E X B drifts on the ionization, as shown in (A). The low emission is associated with the prereversal enhancement of the electric field when the ionization is driven upward and little recombination takes place.

due primarily to photoionization excitation of neutral atomic oxygen. These ions are lost by radiation and are quenched by interaction with neutral oxygen atoms, nitrogen molecules, and electrons. Excellent agreement between two independent determinations of the ionization frequency for the reactions confirmed the absolute measurements of the solar flux below 666 A. In this and other ways, the utility of airglow observations from Atmosphere Explorer type satellites as a tool for gathering information about atmospheric parameters was demonstrated.

The emission monitored in the visible airglow from Atmosphere Explorer C showed large enhancement near 75 degrees magnetic latitude on the dayside of the Earth. This enhancement was associated with particle precipitation into the thermosphere from the polar cusp region of the magnetosphere. The concentration of molecular nitrogen was greatest in the area in which airglow increased. Both electrodynamic and particle heating contribute to this peak of molecular nitrogen. A larger increase toward the pole and on the nightside is probably due almost entirely to Joule heating associated with convection from the magnetosphere, which is the same process that is responsible for the polar current system in the E-region.

The relationship between the emission at 4278 A (from ions of molecular nitrogen) and low-energy particle precipitation in the auroral zone was investigated. It was determined that rapid spatial and temporal variations in the aurora produce a wide range of ratios between the auroral intensity and the total electron energy flux as measured from the satellite, especially at low mean energies. A possible explanation is that there are electric fields parallel to the Earth's magnetic field below the altitude at which the satellite made its measurements. Such an accelerating potential would cause a greater fractional increase or decrease in energies of the less energetic electrons than in those of the more energetic electrons and would therefore produce the large variation in the observed ratios.

Data from the retarding potential analyzer were used to show that there are times when the velocity distribution of the major ions is not a thermal distribution. The departures were observed most frequently at high latitudes when the ion temperature exceeded 1500 K and at altitudes below the peak ionization of the F2-layer. The effect was believed to originate from the combined action of strong magnetic fields and collisions of ions with the neutral gas particles.

Ozone volume mixing ratios at different altitudes, as measured by the backscatter ultraviolet instrument, showed only small seasonal variations. These results, obtained from Atmosphere Explorer E data, applied to low latitudes only because the spacecraft was in an orbit of low inclination to the terrestrial equator. Seasonal variation in ozone is small at the equator. A possible effect of chlorine on removing oxygen in the ozone region was identified.

NEUTRAL ATMOSPHERE STRUCTURE AND DYNAMICS

A band of disturbed atmosphere was identified on a global scale extending about 3000 km in longitude and 1000 km in latitude. This band was believed to be the result of a gravity wave originating in the auroral zone and propagating southward. In fact, the variability of the atmosphere was most pronounced throughout the lifetime of Atmosphere Explorer E. In some locations, vertical wind velocities of 80 to 100 meters per second were measured. Horizontal winds of hundreds of meters per second were routinely measured, with peak velocities approaching 350 meters per second. In addition,

wind direction and magnitude were found to change significantly from day to day. Sometimes the winds moved with the direction of rotation of the Earth; at other times they moved against it.

The neutral mass spectrometer demonstrated its capability to make *in-situ* measurements of local temperatures and winds and revealed not only variability on a local scale but also that the atmosphere is in a very dynamic state most of the time.

The data from the Atmosphere Explorers considerably improved our understanding of the annual and diurnal variations in the thermosphere. San Marco had provided some data for modeling the dynamics of the thermosphere, but mainly at high altitudes above 200 km. The Atmosphere Explorers provided much information about the region above 150 km and incoherent scatter radar data down to the 120-km level. A new model used these data to predict conditions and show the annual variation within the thermosphere expected at 45 degrees north latitude. The data gathered by the Atmosphere Explorers agree extremely well with the new model of the thermosphere that derives the winter helium bulge and provides temperature estimates that agree remarkably well with those derived from radar data.

However, the calculations and comparisons have shown that departures from diffusive equilibrium in the lower thermosphere do exist. There are two competing theories for these departures. One is that changes occur in the height of the turbopause; the other relies on circulation dynamics. Not only is there a diurnal variation in the thermosphere, but also one that occurs twice each day. The latter variation is difficult both to measure and to predict, but it may actually hold the greatest promise of our understanding much of the physics of the thermosphere because the net semidiurnal wave may reflect a competition between a wave rising from below and waves excited within the thermosphere.

The open-source neutral mass spectrometer investigated minor constituents of the neutral atmosphere. The investigators did not find a large seasonal variation in the amount of molecular oxygen such as that implied from interpretations of incoherent radar backscatter measurements from the ground. Atmosphere Explorer D provided some excellent measurements of latitudinal distribution of molecular oxygen. The behavior of this gas proved to be similar to that of molecular nitrogen from the South Pole to about 40 degrees north latitude. Above that latitude, however, the oxygen was enhanced more than that expected from the observations of the nitrogen. An explanation relied on the effects of photodissociation. This high northern latitude feature of oxygen concentration was also seen in the ionized oxygen data and appeared to occur at various local times on the dayside of the planet without regard to the season.

At summer solstice, the maximum of atomic nitrogen in the thermosphere, which occurs at about 50 degrees north latitude, is approximately six times greater than the summer hemisphere minimum. Near the winter solstice, the maximum-to-minimum ratio is about eight. These differences are similar to changes in magnitude over a daily period.

Although the detection of neon in the thermosphere was complicated by the fact that doubly charged argon appears in the spectrum at about the same mass position, the amount of neon was deduced from argon ratios and was used to plot a vertical profile of the gas. This profile corresponded quite well with values calculated from the amount of neon at ground level and an assumption that it remained mixed in the atmosphere to at least 100 km.

Argon was more easily identified, but neon and doubly ionized argon can be confused. Argon showed an increase in the summer hemisphere in contrast to the winter enhancement of helium. Neon appeared to have the same profile over a wide range of latitudes and appeared to be relatively unaffected by wind systems, so that only a small winter-to-summer enhancement occurred, probably arising from the seasonal temperature gradient as opposed to seasonal wind systems.

In a period of magnetic disturbance, the Atmosphere Explorer team found that, although neon was hardly affected, the concentration of helium decreased and that of argon increased. The effects were ascribed to winds in the auroral zone driven by Joule heating, which tended to offset thermal enhancement of neon.

Response of the atmosphere to geomagnetic activity was investigated in depth. In November 1974, Atmosphere Explorer C was in the southern hemisphere and an Air Force S-3 satellite was in the northern hemisphere during a magnetic storm. Density and composition variations during the storm showed significant differences in atmospheric behavior as predicted by then-current models of the thermosphere. For example, important localized enhancements were found at high latitudes, indicating that the region well below 200 km was being heated directly.

Large amounts of energy are deposited at high latitudes during geomagnetic storms by processes related to ionospheric currents and particle precipitation. A two-fold increase in molecular nitrogen was observed at 160 km during the onset of a storm. This increase was unexplained solely by an increase in temperature. It possibly involved convection effects and variation on the height of the homopause.

Density measurements made from the accelerometers onboard the spacecraft produced an

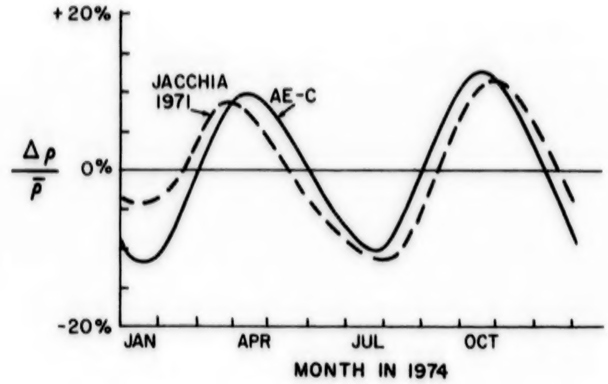

Figure 66. The semiannual density of the thermosphere at 160 km is plotted as the bold curve derived from observations made by instruments carried by Atmosphere Explorer C. The dotted curve shows a model of the atmosphere derived by Jacchia in 1971 for this same semiannual variation in density.

empirical model of the lower thermosphere (figure 66). Information was obtained on how quickly the thermosphere density responds to a geomagnetic disturbance. A time delay of about 3 hours was measured, after which the atmosphere appeared to respond simultaneously from the Equator to midlatitudes.

The Atmosphere Explorer program established the ion chemistry of the thermosphere with good consistency among the various experiments and their measurements. However, the energy processes were not so clearly defined, with the result that the scientists differed in their views about the various transport processes involved. The difficulty appeared to be that the processes do not necessarily originate within the thermosphere or were outside the region in which the measurements were being made by the satellites.

One of the problems was that there was no definitive information about wind systems in the lower thermosphere, where there is significant coupling between the lower atmosphere and the thermosphere, nor were there good measurements to disentangle the temporal and

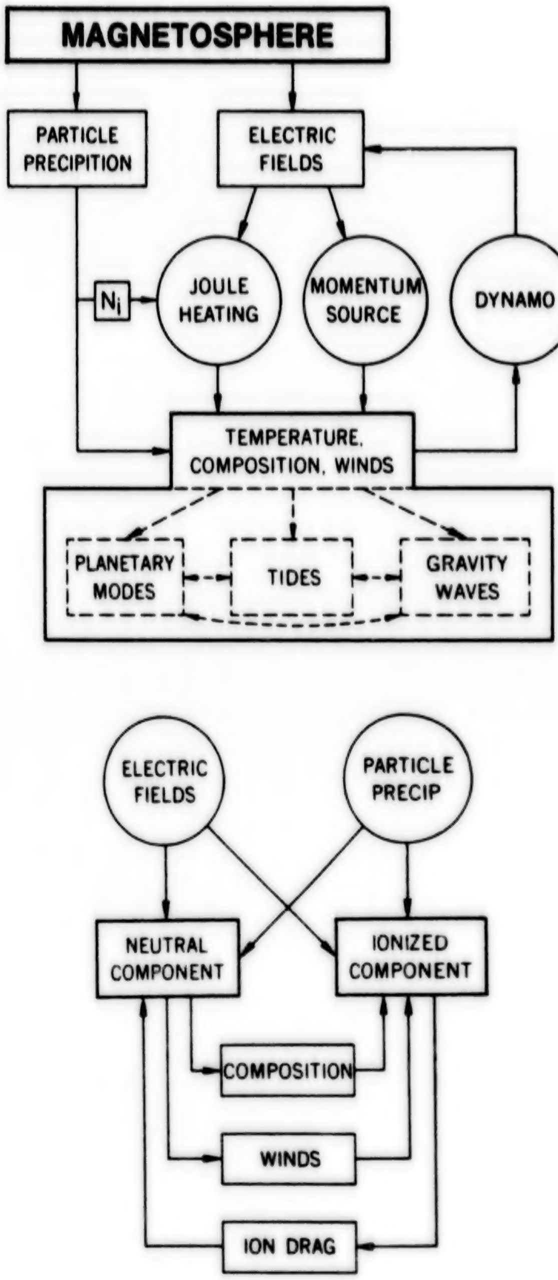

Figure 67. Block diagrams showing the coupling that takes place between the magnetosphere and the thermosphere.

spatial variations. One thing became clear: the concept of diffusive equilibrium was no longer valid for thermospheric composition.

Figure 67 shows the more important coupling processes between the magnetosphere and the thermosphere that are involved in generating magnetic storms in the atmosphere. Indeed, the magnetosphere is clearly the source of particles that dump energy into the lower thermosphere down to 100 km. The particles are a source of ionization and increased conductivity that significantly contribute to Joule heating.

Neutral atmospheric density profiles showed a wave-like structure that is interpreted as being due to propagating gravity waves. These waves do not seem to appear in preferred geographical locations, but they appear to coincide with regions of high winds in the upper troposphere. The waves probably originate in the troposphere, from which they move upward into the thermosphere.

Dynamo electric fields, produced by wind systems in the lower thermosphere, mask the electric fields that originate from the magnetosphere. Joule heating, ion drifts, and dynamo electric fields produce a wide spectrum of planetary scale waves in the thermosphere, tides, and gravity waves. In turn, they are all significantly coupled with each other. Gravity waves may be important to the global redistribution of energy. The ionized and neutral components of the thermosphere are coupled through changes in composition, winds, and ion drag.

There is clear indication of the global redistribution of constituents by a Hadley cell circulation in which minor and lighter constituents are removed from the auroral zone and transported toward the equator. Helium appears to be transported from the poles toward the equator at high altitudes and to be returned at low altitudes. Because helium cannot diffuse upward through nitrogen, an important vertical diffusion barrier exists. Therefore, helium piles up in the equatorial region and decreases at the poles (figure 68). The data from the satellites clearly shows these concentrations. For oxygen,

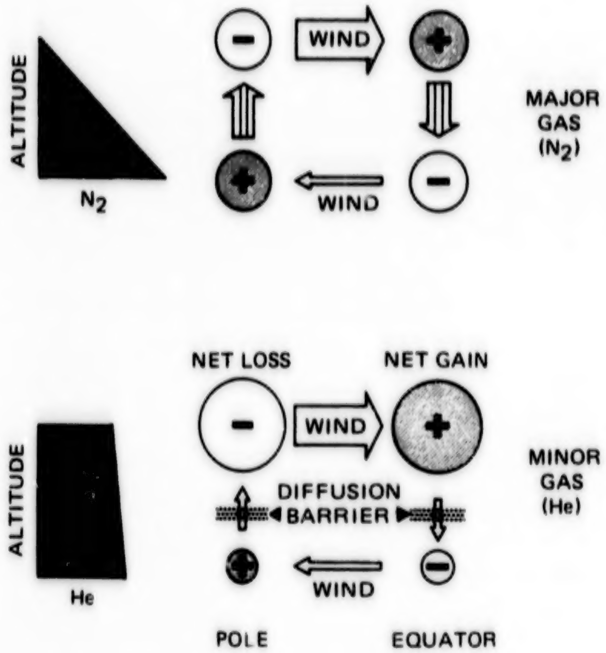

Figure 68. The process of wind-induced diffusion that results in concentrations and depletions of constituents between pole and equator is shown diagrammatically.

chemical loss processes are of more importance than wind transport processes around 250 km, but wind diffusion is important below 220 km.

COLLABORATIVE STUDIES

The Atmosphere Explorer was the first satellite to carry an airglow photometer with the capability to fly below the F-region airglow emission and to look up at the airglow from below. This provided a unique opportunity to compare ground-based observations with those from the spacecraft. Although conditions had to be just right–a pass close to an observatory, no rain, no moonlight–the investigations acquired some very useful data. The nighttime ionization source had been detected by the ground-based observations, but it could not be studied in depth without the Atmosphere Explorer observations. The satellite's instruments located the particle precipitation and the ions in the intermediate E-layer. Moreover, the satellite showed that the particle flux is extremely variable. As a result, an additional source of airglow radiation was identified that had not previously been reported. This source was at 4278 A and was subsequently detected from the Arecibo, Puerto Rico, ground station. However, doubts were cast on the true nature of the observation as showing emission from nitrogen by particle-impact ionization, and it was further speculated that the emission arose from photoionization in the E-region by scattered radiation at 304 and 584 A, the same radiation that is responsible for maintaining the nighttime E-layer.

Since the early days of satellite measurements, there have been reports of large fluxes of energetic ions and electrons at the lower fringes of the radiation belt near the magnetic equator. Observations with an electrostatic analyzer on board an ISIS spacecraft indicated a flux of electrons and protons in the 1- to 5-keV region. Analysis of Atmosphere Explorer data, however, did not reveal any such flux near the magnetic equator, even though the conditions were near those experienced by other satellites.

Atmosphere Explorer C made measurements within the midlatitude trough, which is characterized by a narrow region of reduced ion concentration in the F-region situated near 60 degrees invariant latitude on the nightside of the Earth. The observations revealed a variety of dynamic, chemical, and thermal phenomena that are often associated with depletions of ions in the trough. Large ion-drift velocities were also measured. These measurements emphasized the important role that the convective magnetic field of the magnetosphere must play in depleting ionization at midlatitudes.

Langmuir probe measurements of electron temperature and electron density permitted the identification of regions around the globe at which unusual effects occur (figure 69). At higher latitudes on the dayside of the Earth,

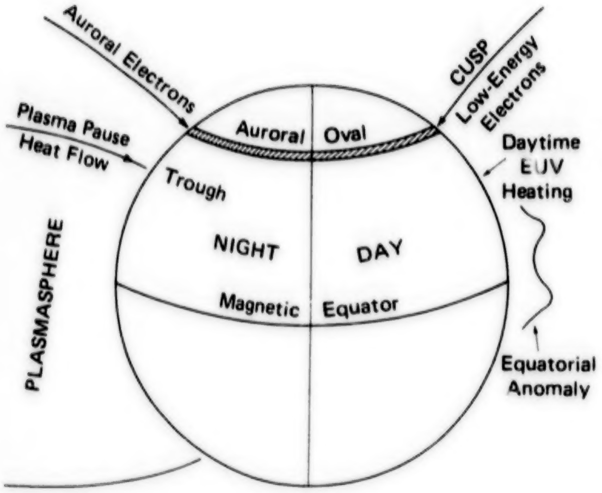

Figure 69. Regions of the ionosphere in which unusual changes in electron temperature and density occur. These changes were measured by the Atmosphere Explorer satellites.

precipitation of low-energy electrons in the cusp region causes a substantial increase in electron temperature. On the nightside, some heating effects arise from precipitation in the auroral oval, but temperature of the electrons is less than on the dayside of the oval.

Electron heating also occurs in the lower F-region at night, which coincides with the mid-latitude trough where heat is being conducted downward from the plasmasphere. The trough actually corresponds to the plasmapause on the night hemisphere. The local cooling process for electrons is much less efficient at low electron densities, whereas heat conduction is almost independent of the electron densities. Heat from the plasmasphere is therefore able to reach the lower F-region without being entirely lost by local cooling. Moreover, the local ions in the trough may at times act as a source of heat for the electrons rather than as coolant to them because the strong electric fields in the vicinity of the trough elevate the temperature of the ions.

It was also discovered that the equatorial anomaly, as observed below the peak of ionization of the F2-region, shows asymmetries from hemisphere to hemisphere that vary with longitude and season. These asymmetries probably arise because of neutral winds in the thermosphere flowing away from the region at which the Sun shines directly down on the Earth–the subsolar point (figure 70).

The Atmosphere Explorers investigated ionospheric irregularities in ion concentrations and in ion drifts. Although irregularities were found at all latitudes and local times, their amplitudes are usually small most of the time at midlatitudes and on the dayside at low latitudes. Irregularities are present at all times from the auroral oval to the poles. The most intense irregularities in number density occur at night within 25 degrees of the magnetic dip equator,

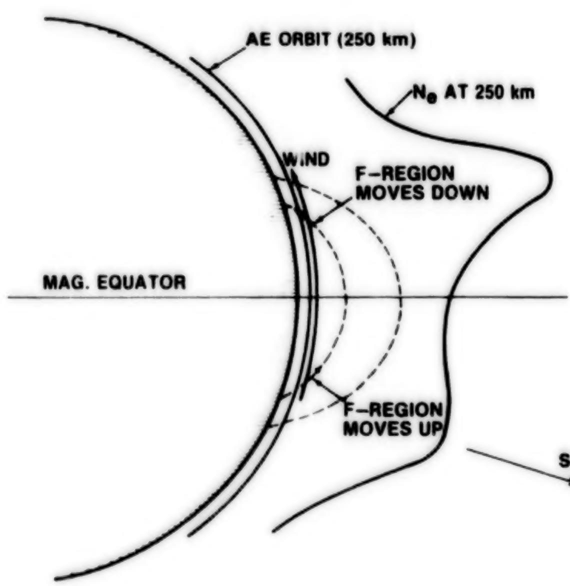

Figure 70. Winds flowing northward from the subsolar point lift the F-region in the summer hemisphere, but drive it downward in the winter hemisphere. As a result, the equatorial anomaly observed just below the peak of the F-region is asymmetrical, with the larger peak located in the winter hemisphere. A typical Atmosphere Explorer C path through this region at 250 km is shown.

with more occurring at the equinoxes than at the solstices.

Other investigators studied the flow of hydrogen in the thermosphere. It was concluded that, although some uncertainty still exists about the precise magnitude of the vertical movement of hydrogen in the daytime thermosphere, there is little doubt that the observed flux is significantly greater than that needed merely to offset losses of hydrogen from the top of the atmosphere into space. It is still not known where the excess hydrogen goes.

The diurnal and seasonal variations in neutral hydrogen appear to be caused by a global minimum concentration of hydrogen that occurs in the thermosphere in the daytime summer hemisphere toward the pole from the subpolar point. A corresponding nighttime maximum occurs at high winter latitudes. The hydrogen concentration at midlatitudes in winter is about twice as great as that in summer for both nighttime and daytime conditions. This seasonal increase is quite nonlinear with latitude. The observed diurnal variation at winter midlatitudes is a daytime concentration of about twice that at night. In the summer hemisphere, the diurnal variation is about three times and is seen at the daytime subsolar latitude. The Atmosphere Explorer measurements also showed that there is an enhancement in the thermosphere of deuterium relative to hydrogen, but it is not as large as was earlier believed.

Temperature data show that the heating and energy transfer patterns in the thermosphere during and following a major magnetic disturbance are quite complex. Distinct latitude and longitude variations extend down to 150 km. Solar activity strongly affects the temperature of the exosphere, changing it from 800 K at a period of low solar activity to 1200 K at high solar activity.

The Atmosphere Explorer data have also been of great use to studies of auroral physics by allowing better predictive modeling of auroral features and detailed analysis of specific cases of auroral activities, correlating with ground-based and rocket observations.

The main scientific results from the Atmosphere Explorer missions include the following:

- Photochemical models of the ionosphere were significantly improved, and coordinated studies of the dynamics of the thermosphere showed that close coupling occurs among the ionosphere, thermosphere, and magnetosphere, especially at high latitudes.
- Routine direct measurements on a global scale of atomic and molecular oxygen and nitrogen permitted seasonal, diurnal, and magnetic storm effects on the constituents to be determined.
- A comprehensive set of data were gathered during the minimum of the 11-year solar cycle. These data have been incorporated into a global scale model of the neutral constituents and temperatures of the thermosphere.
- Coordinated measurements of solar flux, photoelectron spectra, and ion and neutral concentrations provided data that have demonstrated consistency with theoretical descriptions.
- A description of the ion motions in the auroral regions was obtained that proved to be consistent with concepts of auroral circulation.
- Midnight neutral wind reversal and temperature maximum in the equatorial region was shown to be consistent with global circulation patterns.

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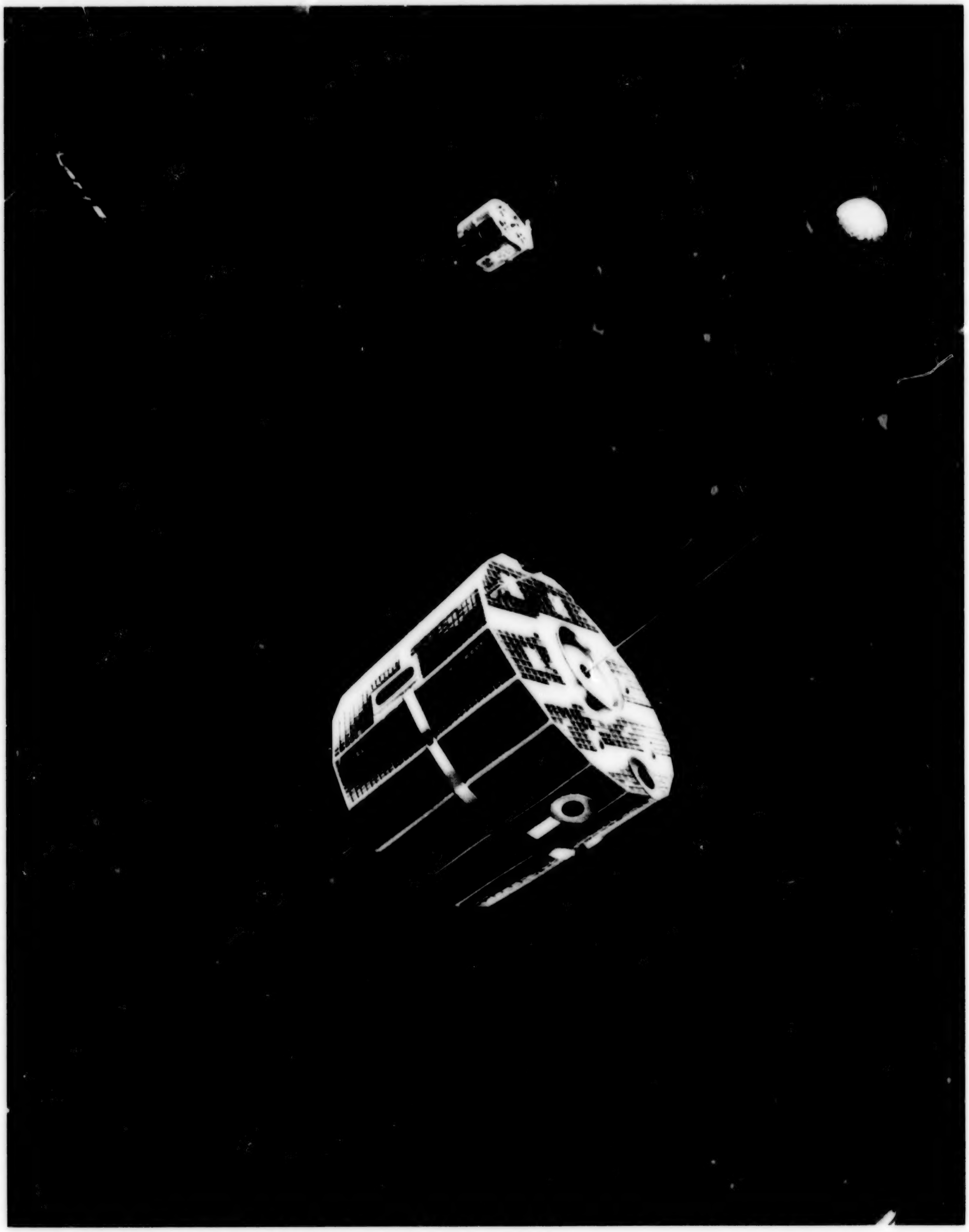

Figure 71. The mission of Dynamic Explorer complements that of the Atmosphere Explorers (courtesy of RCA).

- A comprehensive description of solar flux spectra through a major portion of a solar cycle was obtained.

- An extensive set of ozone measurements has been accumulated to complement data obtained by earlier satellites. These measurements are important to detecting man-caused changes in the layer.

- The satellites demonstrated that multi-instrumented aeronomy studies can be performed by satellites at altitudes as low as 130 km.

- The Atmosphere Explorer satellites carried photochemistry and the microphysics of local processes as far as they can be taken with present accuracies of measurement. Emphasis in aeronomy is now shifting to macrophysics or global dynamics. The Atmosphere Explorers provided a wealth of new information that has permitted scientists to frame specific new questions, particularly about the dynamics and energy processes of the thermosphere. The Dynamics Explorer provided the next thrust into complete understanding of this highly complex region of Earth's environment.

EPILOGUE

NASA's Dynamics Explorer (figure 71) program consists of two spacecraft in polar orbits–one in high orbit, the other in low orbit. The high-orbit satellite makes measurements extending from the hot magnetospheric plasmas through the plasmasphere to the cool ionosphere. The low-orbit satellite makes its measurements in the cool ionosphere and the thermosphere. The two satellites thus measure electric-field-induced convection, magnetosphere/ionosphere electric currents, direct energy couplings, mass coupling, and wave/particle/plasma interactions.

Building on the experience of Atmosphere Explorer, the Dynamics Explorers are also supported by a dedicated central computer in a data handling system that permits science investigators to operate from terminals at their facilities. Some of these terminals are further augmented by minicomputers at the remote sites.

Thus, the Dynamics Explorer continues the broad solar/terrestrial physics program in which the Atmosphere Explorers played such an important role.

The upper atmosphere has been called the frontier to space, but it might also be called the protective membrane of the living cell of Earth. It diffuses into the cell the life-giving energy from the Sun, and it retains within the cell the environment necessary for all life to flourish.

Through these programs, NASA is gaining an increased understanding of the important environment of the Earth high above our heads–the cell membrane of planet Earth. As our understanding increases, mankind achieves a position of being able to prevent accidental contamination of the upper atmosphere and upsetting the delicate global balance of our near-space environment.

APPENDIX A

ATMOSPHERE EXPLORER PROJECT PERSONNEL

The Atmosphere Explorer Project, documented in this book, was made possible by the efforts of many individuals (then in the positions listed below) at NASA Headquarters, the Goddard Space Flight Center, and RCA Astro Electronics. The investigators are deeply grateful to the individuals who contributed to the original AE concept and the spacecraft design, development, fabrication, testing, launch, operations, data processing, and management. All of these factors were essential to the scientific goals of the AE Project.

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APPENDIX B

ATMOSPHERE EXPLORER CONTRACTORS

RCA Corporation, Astro-Electronics Division, Atmosphere Explorer Spacecraft

McDonnell Douglas Astronautics Co., Delta Launch Vehicles

Odetics, Tape Recorders for Spacecraft

Perkin Elmer, Analyzer Tubes

Ball Brothers Research Company, Solar EUV Photometer

Universal Monitor, Cylindrical Electrical Probe

Aero-Geo-Astro, Ion Spectrometer

Central Computer and Data System, Xerox Data Systems

Various Investigators' Universities, Scientific Experiments

APPENDIX C

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B. In Press

*1. Gross, S. H., C. A. Reber, F. Huang, "Large Scale Waves in the Thermosphere Observed by the AE Satellites," IEEE Trans. Geos. Remote Sensing July 1984, in press.

2. Richards, P. G., and D. G. Torr, "Comparison of 0-60 eV Electron Impact Cross Sections for O and N_2 Deduced from Atmosphere Explorer Ionospheric Photoelectron Flux and Solar EUV Flux Measurements with Laboratory and Theoretical Cross Sections, J. Geophys. Res., revised May 1983.

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II. ATMOSPHERE EXPLORER TALKS

		No. of Papers
1.	NATO Advanced Study Institute on Ion-Molecule Interactions, June 1974.	1
2.	Spring 1974 AGU Meeting, Washington, D.C., April 1974.	13
3.	Fall 1974 AGU Meeting, San Francisco, California, December 1974.	20
4.	COSPAR, Sao Paulo, Brazil, June 1974.	2
5.	AIAA 13th Aerospace Sciences Meeting, Pasadena, California, January 1975.	9
6.	57th Annual Meeting/June of AGU, Washington, D.C., June 1974.	30
7.	IAGA and IUGG Meeting, Grenoble, France, August-September 1975.	18
8.	COSPAR, Varna, Bulgaria, May 1975.	2
9.	Magnetospheric Particles and Fields, 1975, Summer Advanced Study School, Graz, Austria, August 1975.	1
10.	Topical Conference on Magnetospheric Models, San Diego, California, May 1975.	1
11.	IX ICPEAC, Seattle, Washington, July 1975.	1
12.	21st International Instrument Symposium, Philadelphia, Pennsylvania, May 1975.	1
13.	AAS/AIAA Astrodynamics Specialist Conference, Nassau, Bahamas, July 1975.	1
14.	Fall 1975 AGU Meeting, San Francisco, California, December 1975.	16

*Guest Investigator

II. ATMOSPHERE EXPLORER TALKS (Cont'd)

		No. of Papers
15.	The James Arthur Annual Lecture on the Sun, May 1975.	1
16.	1975 Spring Annual Meeting, AGU, Washington, D.C., April 1976.	16
17.	COSPAR, Philadelphia, Pennsylvania, June 1976.	8
18.	International Symposium on Solar Terrestrial Physics, Boulder Colorado, June 1976.	4
19.	Second Magnetospheric Cleft Symposium, St. Jovite, Canada, October 1976.	2
20.	Second Symposium on Optical Emissions in the Atmosphere, Stura Zagora, Bulgaria, May 1976.	1
21.	21st Annual Conference of the South African Institute of Physics, July 1976.	1
22.	1976 Meeting of the Heat Transfer and Fluid Mechanics Institute, Davis, California, June 1976.	1
23.	AE Symposium, Bryce Mountain, Virginia, October 1976.	41
24.	1976 Fall Annual AGU Meeting, San Francisco, California, December 1976.	10
25.	1977 Spring Annual Meeting, AGU, Washington, D.C., May 1977.	17
26.	10th International Conference on the Physics of Electronic and Atomic Collisions, Paris, France, July 1977.	1
27.	IAGA Symposium, Seattle, Washington, August 1977.	8
28.	NATO Advanced Study Institute on Dynamical and Chemical Coupling of Neutral and Ionized Atmosphere, Norway, April 1977.	1
29.	1977 Fall Annual AGU Meeting, San Francisco, California, December 1977.	3
30.	1978 Spring Annual AGU Meeting, Miami, Florida, April 1978.	7
31.	13th ESLAB/COSPAR Symposium, Innsbruck, Austria, May 1978.	6
32.	23rd Annual Conference of the South African Institute of Physics, June 1978	1
33.	AE Symposium II, Bryce Mountain, Virginia, October 1978.	54
34.	1978 Fall Annual AGU Meeting, San Francisco, California, December 1978.	2

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II. ATMOSPHERE EXPLORER TALKS (Cont'd)

		No. of Papers
35.	1979 Spring Annual AGU Meeting, Washington, D.C., May 1979.	13
36.	Boundary Layer Conference, Alpbach, Austria, June 1979.	2
37.	Chapman Conference on Waves and Instabilities in Space, August 1979.	1
38.	27th Symposium of the Electromagnetic Wave Propagation Panel of AGARD on The Physical Basis of the Ionosphere, in the Solar-Terrestrial System, Pozzuoli, Italy, October 1980.	3
39.	National Radio Science Meeting, URSI, Boulder, Colorado, November 1979.	2
40.	1979 Fall Annual AGU Meeting, San Francisco, California, December 1979.	2
41.	Satellite Beacon Symposium, Warsaw, Poland, May 1980.	1
42.	1980 Spring AGU Meeting, Toronto, Ontario, Canada, May 1980.	8
43.	COSPAR-23, Budapest, Hungary, June 1980.	4
44.	Chapman Conference on Formation of Auroral Arcs, Fairbanks, Alaska, August 1980.	1
45.	1980 Fall AGU Meeting, San Francisco, California, December 1980.	9
46.	AMS Conference on the Upper Atmosphere, San Diego, California, January 1981.	1
47.	URSI, Boulder, Colorado, January 1981.	2
48.	1981 Spring AGU Meeting, Baltimore, Maryland, May 1981.	6
49.	IAGA, Edinburgh, Scotland, August 1981.	4
50.	IAMAP Hamburg Assembly, Federal Republic of Germany, August 1981.	1
51.	EGS Uppsala Assembly, Sweden, August 1981.	1
52.	XXth General Assembly of URSI, Washington, DC, August 1981.	2
53.	Workshop on Thermosphere Dynamics, NASA/GSFC, Greenbelt, Maryland, October 1981.	3
54.	1981 Fall AGU Meeting, San Francisco, California, December 1981.	7

II. <u>ATMOSPHERE EXPLORER TALKS</u> (Cont'd)

		No. of Papers
55.	1982 Spring AGU Meeting, Philadelphia, Pennsylvania, May 1982.	3
56.	1982 Fall AGU Meeting, San Francisco, California, December 1982.	1
57.	1983 Spring AGU meeting, Baltimore, Maryland, May 1983.	2
58.	1983 Fall AGU Meeting, San Francisco, California, December 1983.	2
59.	7th International Symposium on Equatorial Aeronomy, Hong Kong, March 1984.	1
60.	Ionospheric Effects Symposium, Alexandria, Virginia, May 1984.	1

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